THE GEOLOGY OF THE PRECAMBRIAN ROCKS OF LA HAGUE, MANCHE, FRANCE

by

G.M. Power M.Sc.

Thesis submitted for the degree of

Doctor of Philosophy,

The University of Keele,

October 1974.

ABSTRACT

The Precambrian rocks of La Hague have been divided into three areas of older gneisses, an orthogneiss complex intrusive into these gneisses and a series of post-tectonic granitic rocks.

The gneisses of the Nez de Jobourg, Omonville and Gréville areas are shown to have had a similar evolutionary history. Evidence is presented for an early series of semi-pelitic sediments together with basic rocks, possibly lavas, into which granitic rocks were intruded. Deformation under low pressure amphibolite facies conditions resulted in the formation of a gneissose banding. The 2620m.y. age recorded by Leutwein et al., (1973) is tentatively assigned to this event although it may date the production of the main foliation under amphibolite facies metamorphism which followed. The Nez de Voidries quartz dioritic gneiss and the Nez de Jobourg granodioritic gneiss were emplaced at a late stage during this second deformation. A third deformation formed small scale asymmetric folds of the main foliation. This deformation may have been preceded and was certainly followed by emplacement of basic dykes.

The Thiebot complex, intruded next, is shown to consist of the Moulinet and Jardeheu quartz dioritic gneiss, the Thiebot granodioritic gneiss and the Red granitic gneiss. Chemically and petrographically these rocks form a calc-alkaline series and could have originated by equilibrium fusion of a lower crustal source and fractional crystallization at a higher level. The K-feldspar of the Red granitic gneiss is dominantly only intermediate microcline whilst the Thiebot granodioritic gneiss usually contains both monoclinic K-feldspar and intermediate microcline. This is interpreted as a primary variation and unlikely to be the result of reheating. It is suggested that the foliation in the

Thiebot complex was formed close to the time of intrusion.

The Omonville streaky gneiss cuts the Jardeheu quartz dioritic gneiss. It is normally uniform in chemical and mineralogical composition but locally exhibits strong fractionation.

Brioverian schists at Landemer and Baie de la Querviè̀re are younger than the gneisses of the Gréville area but their age relations to the Thiebot complex cannot be established. It is shown that they have suffered an early and a main phase of deformation under greenschist facies conditions and also contain later minor structures. The gneisses of the Gréville area are sheared and this shearing appears most intense near the schists. It is argued that this was principally produced during the main deformation of the schists although some shearing may be of post-Cambrian origin.

The St. Martin monzonite pre-dates the St. Germain granite and may be older than the other post-tectonic granites. It is characterised by K-feldspar megacrysts and fine grained green inclusions. As suggested by Jérémine (1924), the inclusions probably represent an earlier phase produced from the same magma.

The Northern granites are demonstrated to form a related series of intrusive phases emplaced in the order, meladiorite, leucodiorite, Houffet granodiorite, La Becchue quartz diorite, St. Germain granite and then the Cap de la Hague granodiorite and Ecuty granite, although the order of precedence of these last two is not known. Each phase is shown to have a distinctive mineralogical and chemical composition. Together, although not in strict sequence of intrusive age, they form a calc-alkaline series with the Ecuty granite showing strong fractionation of major and trace elements. The sequence of structural states of the K-feldspars in the later phases is consistent with that found in many series of granitic rocks and conditions were particularly suitable for the production of maximum microcline in the Ecuty granite. There is evidence for sodium metasomatism in the St. Germain granite, possibly related to the emplacement of the Cap de la Hague granodiorite. Local zones of cataclastic deformation occur in the granites and may result from post-Cambrian movements.

The Cambrian sediments suggest post-tectonic molasse type sedimentation. New descriptions emphasise the importance of thrusting of the Cambrian over the underlying rocks and nowhere is there unequivocal evidence of an original undisturbed sedimentary surface between Precambrian and Cambrian.

The foregoing descriptions enable the strong similarities in geological history between La Hague and the nearby Channel Islands to be recognised and discussed.

ACKNOWLEDGEMENTS

This study was made possible by the provision of a Demonstratorship in the Department of Geology, University of Keele. I thank Professor Cope and all the members of the Department for their assistance and advice.

Mr. D. Leverett and his technical staff at Keele helped in many ways, in particular Mr. D. Kelsall by his skilled photographic work. The Department of Geology, Portsmouth Polytechnic provided material and technical assistance for the final preparation of the thesis. Mr. M. Chrismas made the plates and Mr. J. Davidson drafted many of the figures.

Professor Dr. F. Leutwein, University of Nancy, carried out isotopic age determinations on rocks from La Hague collected during this work and by so doing made a fundamental contribution to our knowledge of the area. Mme. Danielle Velde readily made available her collection of thin sections of gneisses from La Hague for my study. Mr. A.D. Walton provided the air-photos used as a base for coastal mapping from the Air-photo Library, Department of Geography, University of Keele.

To the above people and to many others not mentioned specifically I am most grateful for their help.

Above all I thank Dr. R.A. Roach for introducing me to the geology of the Armorican Massif, for his inspired instruction in the field and for his time generously given in supervision of this project.

CONTENTS.

CHAPTER 1

INTRODUCTION AND REVIEW OF PREVIOUS WORK

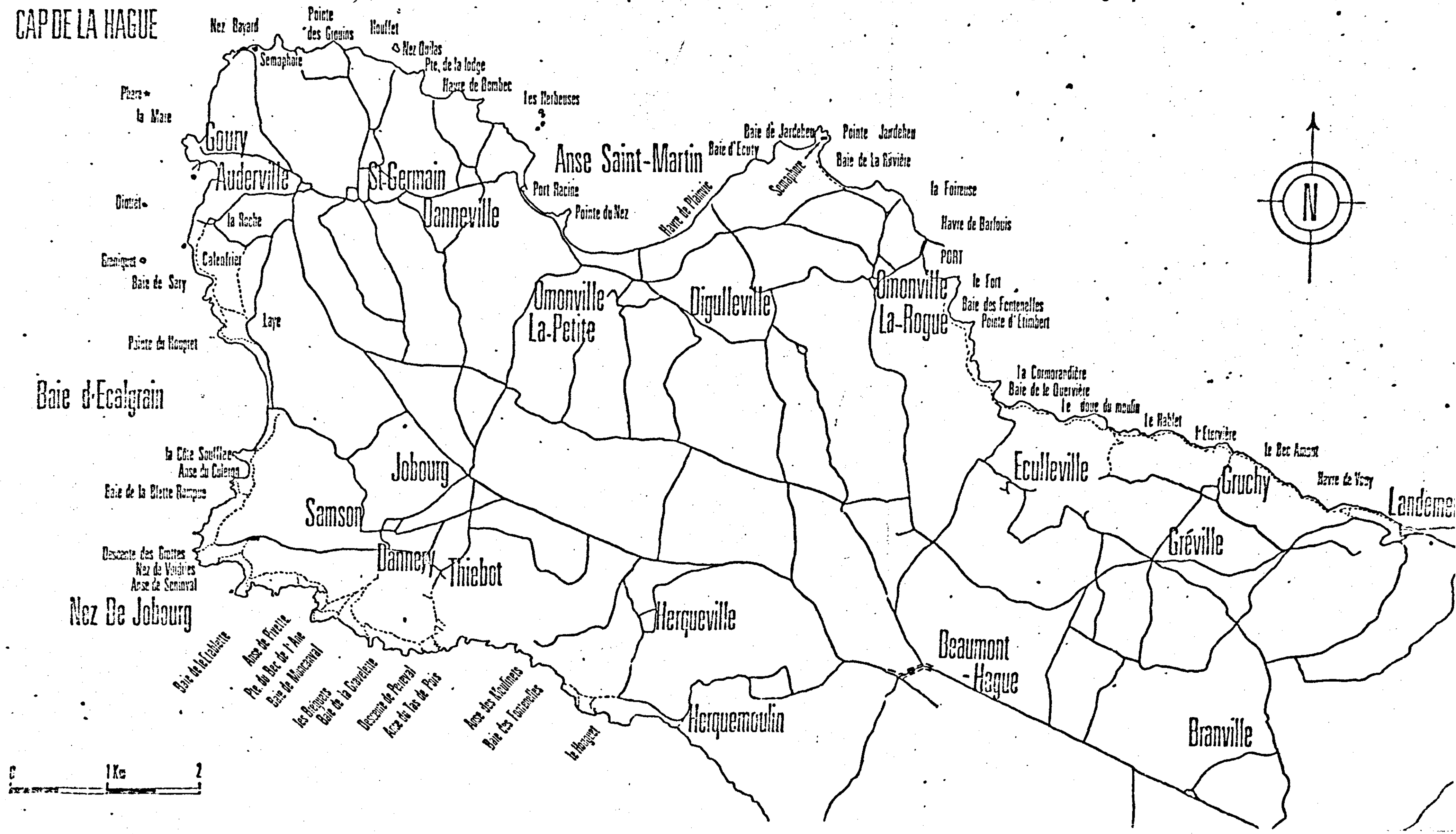
INTRODUCTION

La Hague is an area to the west of Cherbourg at the north-west tip of the Cotentin peninsula, Manche, France. For the purposes of this thesis it has been taken as lying north-west of a line joining Herquemoulin, Beaumont-Hague and Landemer. That is an area of about 70 sq km with sea on three sides giving a coast-line of more than 25 km (see figure 1,1).

It is a region of moderate relief reaching a maximum of nearly 140 m in height, with rounded hills, steep sided valleys and a central plateau. Steep cliffs and rocky coves form the south coast and parts of the west coast. The north coast from Goury to Omonville-la-Rouge is low lying with a wide tidal platform. East of Omonville to Landemer the coast forms a further series of cliffs. The variation in coastal relief broadly reflects the variation in the geology. The areas in which steep cliffs are found are made up of early Precambrian gneisses and later Precambrian granites. The low lying north coast is composed of late Precambrian granites and the central plateau of Cambrian and Ordovician sediments.

La Hague is in the northern part of the Armorican Massif. The introductory chapter first gives a brief outline of the Precambrian geology as already established by others in the north-eastern part of the Massif, although an account of the geochronology is reserved until Chapter 8, and then reviews previous work in La Hague in particular. Chapters 2-7 give an account of the geology of La Hague

Fig.1 La Hague, place names used in text.



as determined during this work (see figure 2.1 for an outline geological map and end maps 1-7 for more detailed information). Finally, Chapter 9 provides a summary of the Precambrian geological events in La Hague established in the previous chapters and suggests comparisons with similar series of events in nearby areas.

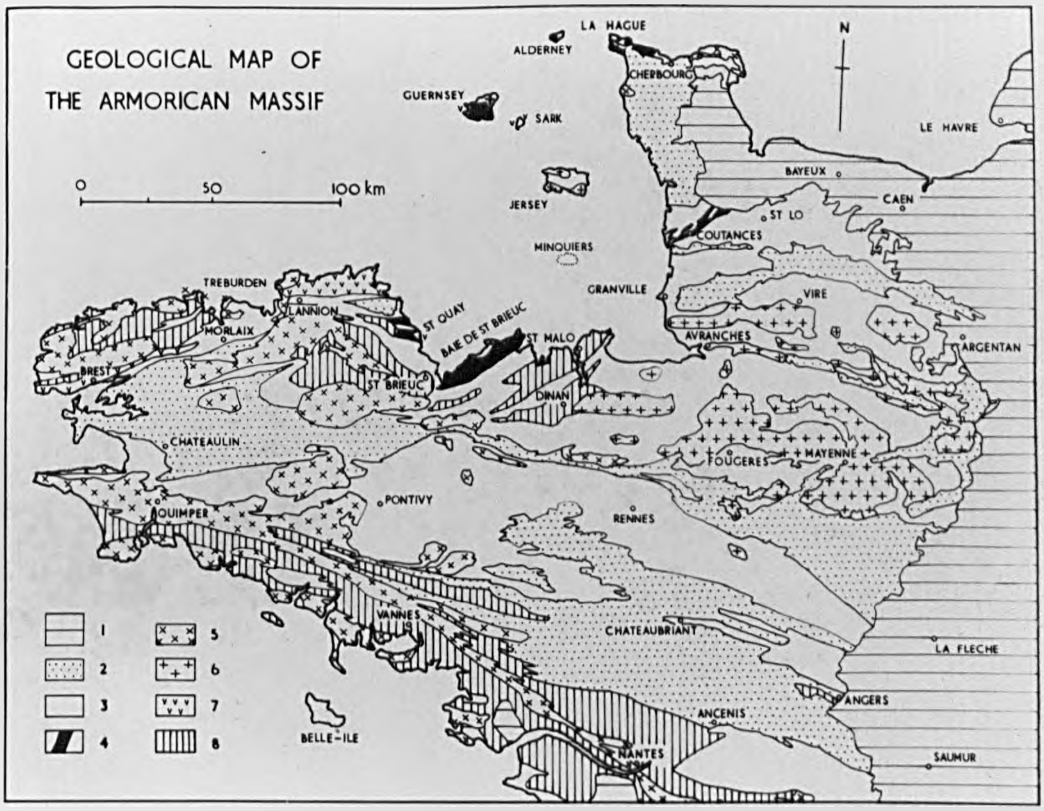
Note: The place names used in this thesis for localities in La Hague have been taken from the 1:25000 Carte de France published by the Ministère des Travaux Publics et des Transports, sheets Cap de la Hague 7-8, Cherbourg 1-2 and Les Pieux 3-4. Most of the names used are shown in figure 1.1 and the spellings may differ from those used in other publications.

THE PRECAMBRIAN GEOLOGY OF THE NORTH-EAST OF THE ARMORICAN MASSIF

The Armorican Massif is the name given to the region of pre-Mesozoic rocks occupying Lower Normandy and Brittany and including the Channel Islands (figure 1.2). It is composed of elongate synclinal areas of Palaeozoic sediments, granitic plutons of Variscan and end Precambrian, Cadomian, age and of Precambrian Brioverian sediments and volcanics. A pre-Brioverian crystalline basement has also been recognised.

The Pentevrian

Cogné (1959) was the first to recognise the presence of a pre-Brioverian crystalline basement. He stated that around the Baie de St. Brieuc, the Erquy ophiolitic series taken as the base of the Brioverian sediments, rested discordantly on an older crystalline basement of granitic gneisses, amphibolites and dioritic migmatites characterised by a NNE-SSW structural trend. He described in some detail the unconformity between these fundamental units at Jospinet on the east side of the Baie de Saint Brieuc.



F I G U R E 1.2

SIMPLIFIED GEOLOGICAL SKETCH MAP OF THE ARMORICAN MASSIF.

(From Roach et al. 1972)

Key:
1. Mesozoic and Tertiary.
2. Palaeozoic supracrustals.
3. Brioverian supracrustals.
4. Pentevrian basement.
5. Hercynian granites.
6. Younger Cadomian granites.
7. Older Cadomian granites.
8. Undifferentiated metamorphic rocks.

The name Pentevrian was given by Cogné to this basal complex as a whole. "A ce, "complexe de base", témoin d'un vieux continent anté-briovérien, je propose de donner le nom de Pentévrien." It is this original usage of the term that is followed in this thesis, as for example used by Roach et al. (1972). Others, e.g. Leutwein (1968a) have restricted the term to refer to a single specific orogenic event at around 1000 m.y. Subsequent to Cogné's original recognition of the Pentevrian other areas have also been considered to be Pentevrian. Graindor (1960a) proposed that as a "working hypothesis" certain rocks of La Hague, Guernsey, Sark and Les Minquiers could be considered similar on both structural and petrological grounds to the Pentevrian of the Baie de St. Brieuc. Cogné (1962) added the Gneiss de Trébeurden to the Pentevrian. Brown, Barber and Roach (1971) concluded that the St. Malo migmatite belt formed part of the crystalline basement on which the Brioverian sediments were deposited and may be broadly equated with the Pentevrian from adjacent areas.

On the basis of the original use of the term the unambiguous assignment of rocks to the Pentevrian may only be made if they may be shown to be structurally distinct from the Brioverian and older than the oldest Brioverian sediments. The most satisfactory demonstration of this is the presence of a major unconformity between the two fundamental units with basal Brioverian sediments positively identified above. Unfortunately this simple situation has not been recognised in many localities. In the relatively few places where the contact between the two fundamental units is exposed the relationship is often complicated by later deformation. As a result other approaches have also been used in order to assign rocks to the Pentevrian. Brown, Barber and Roach (1971) carried out a detailed metamorphic and structural analysis of a small area on the west edge of the St. Malo migmatite belt at Plage de Quatre Vaux and concluded that the migmatites must have been formed before the deposition of the adjacent sediments. Provided that the sediments are definitely Brioverian the migmatites must be Pentevrian. An additional example of the more complex nature of the Pentevrian basement compared with the Brioverian cover and the deformed nature of the Pentevrian-Brioverian contact as a result of Cadomian deformation has recently been described by Ryan (1973) from the Palus Plage area along the west side of the Baie de St. Brieuc.

Isotopic age determinations have not been able to firmly establish the age of the earliest Brioverian sediments but where rocks are shown to be much older than the oldest known Brioverian sediments it is reasonable to assign these to the Pentevrian e.g. the Icart Gneiss on Guernsey, even though they may not be seen in contact with the Brioverian.

Recently Vidal et al. (1971) have presented geochronological evidence that they claim demonstrates that the basal Brioverian Series d'Erquy at Erquy itself is Ordovician in age. This has been supported by identification of a poorly preserved microfauna of Baltisphaeridium sp. and Veryhachium? of lower Ordovician age, in the Series d'Erquy (Deunff et al., 1973). Thus some doubt has been cast on the precise age of the unconformity at Jospinet. The validity of the interpretation of an Ordovician age for the sequence at Erquy has been questioned by Brown and Roach (1972). Whatever the true age of the rocks at Erquy the presence of a pre-Brioverian crystalline basement cannot be seriously in doubt. Structural studies coupled with isotopic age determinations clearly show the distinctive nature of the Pentevrian compared with the Brioverian.

A brief review of these differences is given by Roach et al. (1972).

The Brioverian

The term Brioverian, which was first introduced by Barrois (1895) for a 'system' of 'infracambrian' rocks, is now used for the Upper Proterozoic supracrustal sequence which rests on the Pentevrian crystalline basement and is overlain unconformably by the Cambrian. The evolution of this present definition and the history of research on the series is summarised by Graindor (1957) and Cogné (1962).

The stratigraphic subdivision of the Brioverian of the north-east of the Armorican Massif proposed by Graindor (1957) and modified after Cogné (1970), is given in table 1.1. Cogné (1970) defined a new stage at the base of the Lower Brioverian, l'étage de Cesson-Locquirec, for the conglomerates and arkoses of variable thickness sometimes found beneath l'étage d'Erquy. Graindor (1957, 1964) used the "poundingue de Granville" along with other pebbly mudstones as an important marker horizon representing tillites from a period of Precambrian glaciation whilst Winterer (1964) concluded on the basis of a sedimentological study that it was deposited from a subaqueous mud-flow and that there was not sufficient evidence to determine if it was tilloid in nature.

The Cadomian

The Cadomian was the name given to the orogenic episode responsible for the structural discordance between the Cambrian and the Brioverian (Bertrand, 1921). A summary of how the widespread nature of this discordance was gradually recognised was given by Cogné (1962). More recently, the used of the term Cadomian has been extended to cover all end Precambrian metamorphism and tectonism affecting the Brioverian (Graindor, 1957; Cogné, 1962).

TABLE 1.1

STRATIGRAPHIC SUBDIVISION OF THE BRIOVERIAN

OF THE NORTH-EAST OF THE ARMORICAN MASSIF

(After Graindor, 1957 and Cogné, 1970)

Upper Brioverian X3	L'Étage de la Laize (X3b)	Massive sandstones; thin calcareous sandstones; fine alternations shale and sand-stone.
	L'Étage de Granville (X3a)	Pebbly mudstones; fine grained, thin, light and dark strata.
Middle Brioverian X2	L'Étage de la Villiers-Fossard (X2b)	Alternating laminae of fine grained black shale and grey quartzite.
	L'Étage de la Lande des Vardes (X2a)	Fine grained graphitic quartz-ites (phtanites); black shales; pyroclastics.
Lower Brioverian X1	L'Étage d'Erquy (X1)	Volcanics, predominantly basic; black shales; sandstones.
	L'Étage de Cesson-Locquirec (X1)	Arkoses; conglomerates; feldspathic sandstones. Variable in thickness.

NOTE: Graindor (1957) placed the volcanics of Saint-Germain-le-Gaillard at the base of the Upper Brioverian. Boyer et al. (1972) suggest they are post-Brioverian but older than the Cambrian.

The Cadomian was envisaged to have developed in two stages by both Cogné (1962) and Graindor (1964). An early, pre-Upper Brioverian event was suggested by Graindor (1957) on the basis of the presence of pebbles of phtanite with small scale folds found within the Granville pebbly mudstones and was later named the Constantian phase (Graindor, 1964). This was supported by Roblot's (1962) description of an unconformable boundary between Middle and Upper Brioverian at Quibou and by Jeannette and Cogné's (1968) interpretation that a major discordance exists between Middle and Upper Brioverian on the west side of the Baie de Saint-Brieuc. Cogné (1970) described the folds produced by this early deformation as large, upright, tight isoclinal folds trending E-W. Following uplift, the Upper Brioverian "tillitic" conglomerates, for example the Granville pebbly mudstones, were deposited followed by flysh sedimentation. The whole Brioverian was subsequently deformed during the Viducastian phase (Graindor, 1964) of the orogeny. Cogné (1970) interpreted the red sandstones and conglomerates of the Cambrian as molasse deposits resulting from uplift and erosion of the Cadomian mountain chain.

Roach et al. (1972) stated that neither Bradshaw, Renouf and Taylor (1967) nor themselves had yet found evidence for a major deformational episode equivalent to the Constantian and although local breaks may occur in the Brioverian succession they suggested that all prominent deformational episodes occurred subsequent to the termination of Upper Brioverian sedimentation.

The Brioverian sediments usually show at least two phases of folding as a result of the Cadomian orogeny. The main phase of deformation has often resulted in the development of dominant north-east to east trending folds and foliation. In Finistère (Bishop et al. 1969), the main phase of deformation was followed soon afterwards by intrusion of the Gneiss de Brest and later by metamorphism, locally to almandine amphibolite facies. Post-tectonic granitic intrusion in Finistère is shown by the Renards granite. In the Zone Bocaine of Lower Normany several of these granites (the Mancellian granites) metamophose the Brioverian but are overlain by unmetamorphosed Cambrian sediments proving their post-Brioverian and Precambrian age. (Chauris, Dangeard, Graindor and de Lapparent, 1956).

PREVIOUS WORK ON THE GEOLOGY OF LA HAGUE

Bigot (1882) described his preliminary investigations in La Hague and neighbouring areas. He recognised igneous and metamorphic rocks near Gréville, Omonville-la-Rogue and Nez de Jobourg as forming the oldest parts of La Hague, and that a central zone was occupied by younger sandstones and shales, but did not comment on the relations between these two rock groups. The north and the south coasts were described as being composed of rocks of igneous origin and he included in this group rocks in the Anse du Culeron, which appeared to lift up the sandstones at the south end of the Baie d'Ecalgrain.

Further, more detailed work by Bigot resulted in the publication of the geological map, "Les Pieux" (1900), 1:80,000, C.G.F. No. 16. The sedimentary sequences of La Hague were divided into Cambrian and Lower, Middle and Upper Ordovician with lithological subdivisions of the Cambrian being shown. The old rocks, but now including those of Anse du Culeron, were assigned to the Precambrian and described as grantised or migmatised St. Lô schists, Xla, the oldest sub-division of the Brioverian. The diorite at Pointe Jardeheu and that at Anse des Moulinets were correlated with the diorite on the west of Alderney. The latter was said to be Precambrian because it was overlain by what appeared to be the continuation of the same series of arkoses which had been given a Cambrian age in La Hague. It was suggested that these diorites seemed to be the oldest igneous rocks in the region. On the other hand the Auderville granite which makes up the north-west coast of La Hague was said to enclose recrystallised Cambrian quartzites between La Roche and Goury and must by implication be post-Cambrian in age. This was again mentioned in an account of a Geological Society of France excursion to La Hague (Bigot, 1904) and the Auderville granite was said to inject and metamorphose the Cambrian.

Bigot's account of the 1904 field excursion also included a description of the contact between the granitised St. Lô schists ("Les Pieux", 1900) and Ordovician sandstones at the south end of the Baie d'Ecalgrain. The sandstones were described as being feldspathised and cut by grantitic and aplitic dykes. This would mean that at least some of the granitisation took place after the Ordovician. However nearly twenty years later, with the assistance of Mme. Jérémine, Bigot revised his views on certain aspects of the geology of La Hague. They stated (Bigot and Jérémine, 1923) that the Cambrian and "Silurian" (Ordovician) were never cut by granitic rocks and did not show any sign of contact metamorphism, thus completely reversing Bigot's description of the situation at the south end of Baie d'Ecalgrain (1904). Further, they pointed out that although they still believed in the presence of quartzites enclosed in the Auderville granite there was no evidence that these were Cambrian in age. This meant that the Auderville granite did not have to be post-Cambrian.

In the same paper they confirmed the Precambrian age of the granite with large orthoclase crystals which occurs in Anse St. Martin and also of some of the gneisses of La Hague by identification of pebbles of these rocks in the basal Cambrian conglomerates. Further, in La Hague, neither the Cambrian nor the "Silurian" (Ordovician) was ever seen resting on its original substratum, the contact always being an extremely broken zone within which elements of both formations may be identified. It was not possible, however, to evaluate the importance of this thrusting.

Following these earlier works on field relations several papers by Mme. Jérémine appeared dealing mainly with the petrography of the rocks. Jérémine (1924) described the granite with inclusions occuring at Anse St. Martin and concluded that the granite and the inclusions both originated from the same magna by differentiation at depth. This was followed (Jérémine, 1927) by a paper which described the late basic dykes and gave details of the petrography of dolerites, minette and kersantite.

Prior to the publication of Mme. Jérémine's main work on La Hague (1930) a further excursion to the area by the Geological Society of France was recorded by Bigot (1929). Discussion centred on the nature of the relationship between the Cambrian and the underlying basement. Bigot did, however, include an interesting description of the Precambrian rocks between Landemer and Eculleville. He said that at both these places a similar series of dark schists, sometimes graphitic or calcareous, was recognised in a close relationship with underlying gneisses. The gneisses were interpreted as Brioverian sediments metamorphosed by a Precambrian granite. This metamorphism was not seen in the schists. Superimposed on the gneissose foliation was a cataclastic structure caused by shearing which had also transformed the granite into a foliated rock. It was difficult to distinguish the gneissose rocks of metamorphic origin from those due to shearing.

The publication by Jérémine (1930) of a petrographic study of the rocks of La Hague represented a major advance in the geological knowledge of the area. A description of all known contacts between the Cambrian and underlying rocks was given. It was concluded that the Cambrian was never metamorphosed and that the contracts were often normal although they may show a little movement along them. This is a change in interpretation from Bigot and Jérémine (1923) in which all the contacts were considered to be mechanical. The underlying rocks were considered to represent an ancient peneplaned surface over which the Cambrian transgression took place.

The Precambrian rocks from each of the main areas were described in turn. The intense mechanical deformation was the main feature of the Gréville area and the intrusion of many sheets of foliated granite into the basement gneisses the main feature of the Omonville-la-Rogue area. The basement gneisses of the Nez de Jobourg area contained inclusions of amphibolite and quartzite and in Anse du Culeron contained garnet and sillimanite. The foliated granite and diorite of the south coast at Anse des Moulinets were seen as granites of similar composition but with small differences caused by differentiation of the same magna. They injected former sedimentary rocks and finally suffered shearing in a direction consistently close to north-east.

The Auderville granite was of Precambrian age because recognisable pebbles were found in the Cambrian conglomerates. It was said that there was some variation within this granite but that there was no means of judging if several independent intrusions existed. It was concluded that any variation was produced from one magma by differentiation.

Bigot (1934) in an explanatory note on the second edition of the geological map, "Les Pieux", 1:80,000 C.R.F. No. 16, stated that the

Auderville granite was later than the Cambrian because it enclosed Cambrian sediments between La Roche and Goury but did not produce any fresh evidence for assigning this age to the quartzites. There are few changes from the first edition of this map.

The existence of a relationship between the mineralogy and distribution of the Precambrian crystalline rocks was proposed by Jérémine (1942). She suggested that whilst the rocks west of Omonville-la-Rogue belonged to the deeper kata- or meso- zones of the crust on the basis of their mineral assemblages of plagioclase, amphibole, biotite, garnet and sillimanite the rocks east of Omonville were representative of a higher zone as they contained sericite, chlorite, calcite and albite. The rocks east of Omonville were envisaged to be superposed directly on the gneisses of the deeper zone.

This hypothesis was supported by Graindor (1957) in his work on the Brioverian of the north-east of the Armorican Massif. In this he treated the Precambrian of La Hague as Lower and Middle Brioverian together on the basis that it was difficult to separate them. The schists at Landemer were designated X_{2a}, lower Middle Brioverian, because of their lithological similarity to the Landes des Vardes schists while the shearing in the Gréville block was attributed to post-Brioverian thrusting. The structure of the Precambrian was a plunging anticline. Soon after Cogné (1959) had described the existence of a pre-Brioverian Pentevrian crystalline basement on the south-east side of the Baie de Saint Brieuc, a field excursion again visited La Hague (Graindor, 1959) and Dangeard commented on the similarity between X_{1a}, the oldest rocks of La Hague, and the Pentevrian. He suggested that X_{1a} could be much older than the other Brioverian stages and represent a Pentevrian basement. Graindor (1960a) proposed that the crystalline basement of La Hague could be considered of Pentevrian age as a "working hypothesis". He had previously thought these rocks to be the migmatised base of the Brioverian but following Cogné's establishment of a pre-Brioverian crystalline basement this seemed a much more attractive proposition. According to Graindor (op. cit) the rocks of La Hague were petrographically analogous to those of the Pentevrian and there was a certain structural disharmony between the Brioverian and the Jobourg-Jerdeheu anticline.

The publication of the Cherbourg sheet 1:50,000 C.R.F. Nos. X11-10, X1-10, and the accompanying bulletin (Graindor, 1960b) provided a summary and interpretation of all previous work on La Hague. Graindor cast doubt on the validity of the stratigraphic subdivision of the Cambrian claiming that the "grès feldspathiques" were not lithologically distinguishable from the basal arkoses. He also admitted that although he assigned the dark calcareous schists of Landemer to the Middle Brioverian they might belong to the Lower Brioverian.

The deformation affecting the Palaeozoic rocks was considered important by Graindor (1958, 1960b) and shown to result in large thrusts especially around Cherbourg. Klein (1963) suggested that the movements were smaller than Graindor believed them to be. Coates (1961) attributed the overturning of the syncline in the Baie d'Ecalgrain and the thrusting of the Cambrian over the Ordovician in the north of that bay to one such movement from north to south.

A modern palaeontological and sedimentological study of the Ordovician of the Siouville and Jobourg synclines was carried out by Coates (1965). He suggested that the Cambrian and the Grès Armoricain may be part of a single sedimentary cycle. The Ordovician of La Hague was divided into four distinct sedimentary periods, the open shelf sedimentation of the Grès Armoricain, the inter tidal flat and proximal pro-delta environment of the bioturbate facies of the lower Middle Ordovician, the deeper water, pro-delta slope conditions represented by the Schists à Calymene (upper Middle Ordovician) and the delta platform lagoons and tidal flats of the Upper Ordovician.

Velde, Quaglieri and Kienast (1971) recorded the presence of kyanite in the sillimanite biotite gneisses of Anse du Culeron. They noted that an amphibole-bearing granite cut the pre-existing metamorphic rocks at Pointe du Becdè l'Ane and stated that this same granite was also to be found in the Baie d'Ecalgrain, the Baie d'Etablette and in the Anse du Culeron. They subdivided the metamorphic rocks of the Nez de Jobourg area into three divisions: "unité I", a light coloured granitic rock bearing garnet found in Anse de Seninval and Anse du Culeron; "unité II", the biotite sillimanite gneisses of the south end of Anse du Culeron and also said to form the Nez de Voidries and the tip of the Nez de Jobourg; and "unité III", a varied group of gneisses and amphibolites making up the remainder and containing members not unlike those of unité I and II. The significance of this subdivision was not made clear.

The biotite sillimanite gneiss of Anse du Culeron was shown to contain relict kyanite and garnet and also andalusite which was probably late, besides sillimanite. It was proposed that this proved the gneisses were poly-metamorphic. They suggested that an early metamorphism produced the kyanite and garnet, a fall in pressure resulted in the formation of the sillimanite and a later slight fall in temperature caused andalusite and muscovite to develop. The formation of kyanite was equated with a Pentevrian metamorphism on the basis of Graindor's (1960a) "working hypothesis" that the gneisses were Pentevrian. Graindor's suggestion had been adopted by Cogné (1962) without additional evidence and Velde et al. (1971) quoted Cogné (1962) as authority for the Pentevrian age of the gneisses.

Leutwein, Power, Roach and Sonet (1973) gave the results of geochronological determinations carried out on specimens collected during work for this thesis. These determinations provided an isochron of 2500m.y. ($\lambda_{Rb} = 1.47 \times 10^{-11} yr.^{-1}$) for the gneisses of the Nez de Jobourg and Omonville areas and one of 2200m.y. for those of the Gréville area proving that they all belong to the Pentevrian. An Rb/Sr whole rock isochron for the rocks of the Thiebot complex gave an age of 775m.y. (λ_{Rb} as above). Sb/Sr separate mineral - whole rock isochrons for the same samples gave an age of 580m.y. for uplift and cooling of the Thiebot complex which was supported by K/Ar mineral ages around 550m.y.

<u>Summary</u>

In La Hague three areas of rocks, namely, Nez de Jobourg, Omonville-la-Rogue and Gréville have been recognised as being of possible Pentevrian age on the basis of their structural and petrographic similarities to areas of known Pentevrian basement. Leutwein et al. (1973) have produced geochronological evidence that proves these rocks are Pentevrian.

On the north coast the Auderville granite and the "granite with inclusions" are Precambrian.

The schists at Landemer and Eculleville are considered to be of Brioverian age.

The Cambrian arkoses rest unconformably on the older rocks and the contacts are not considered to show much movement. Thrusting may, however, be important in the tectonic history of the area.

The Ordovician rocks are of shallow water origin.

CHAPTER 2

THE GNEISSES OF THE NEZ DE JOBOURG AREA

INTRODUCTION

From the earliest geological work in the region (Bigot, 1882) three areas of La Hague, each isolated from the others, have been recognised as constituting the oldest rocks. These are the gneisses of the Nez de Jobourg, Omonville and Gréville areas. The location of each of these areas is shown in figure 2.1. In this chapter and chapters 4 and 5 the rocks of each of these areas in turn will be described. However, to assist the geological unity of the descriptions it was thought preferable to include the chapter on the Thiebot igneous complex immediately after that on the Nez de Jobourg area and to include the description of the Landemer schists in chapter 5 on the Gréville area.

The gneisses of the Nez de Jobourg area occur from the south end of the Baie d'Ecalgrain around the coast to the east side of Anse de Pivette at Pointe du Bec de L'Ane. At Baie d'Ecalgrain they are in faulted contact with the Lower Palaeozoic sediments and at Pointe du Bec de l'Ane they are intruded by the Thiebot gneiss (see end map 3). Inland they extend approximately to a line drawn between these two localities but exposure is extremely limited. The inland boundaries are faulted. The gneisses are also found as screens within the Thiebot gneiss complex and at Descente de Perreval on the south coast where the contact between the Thiebot gneiss and the Nez de Jobourg gneisses is exposed.

The Nez de Jobourg gneisses show considerable variation within

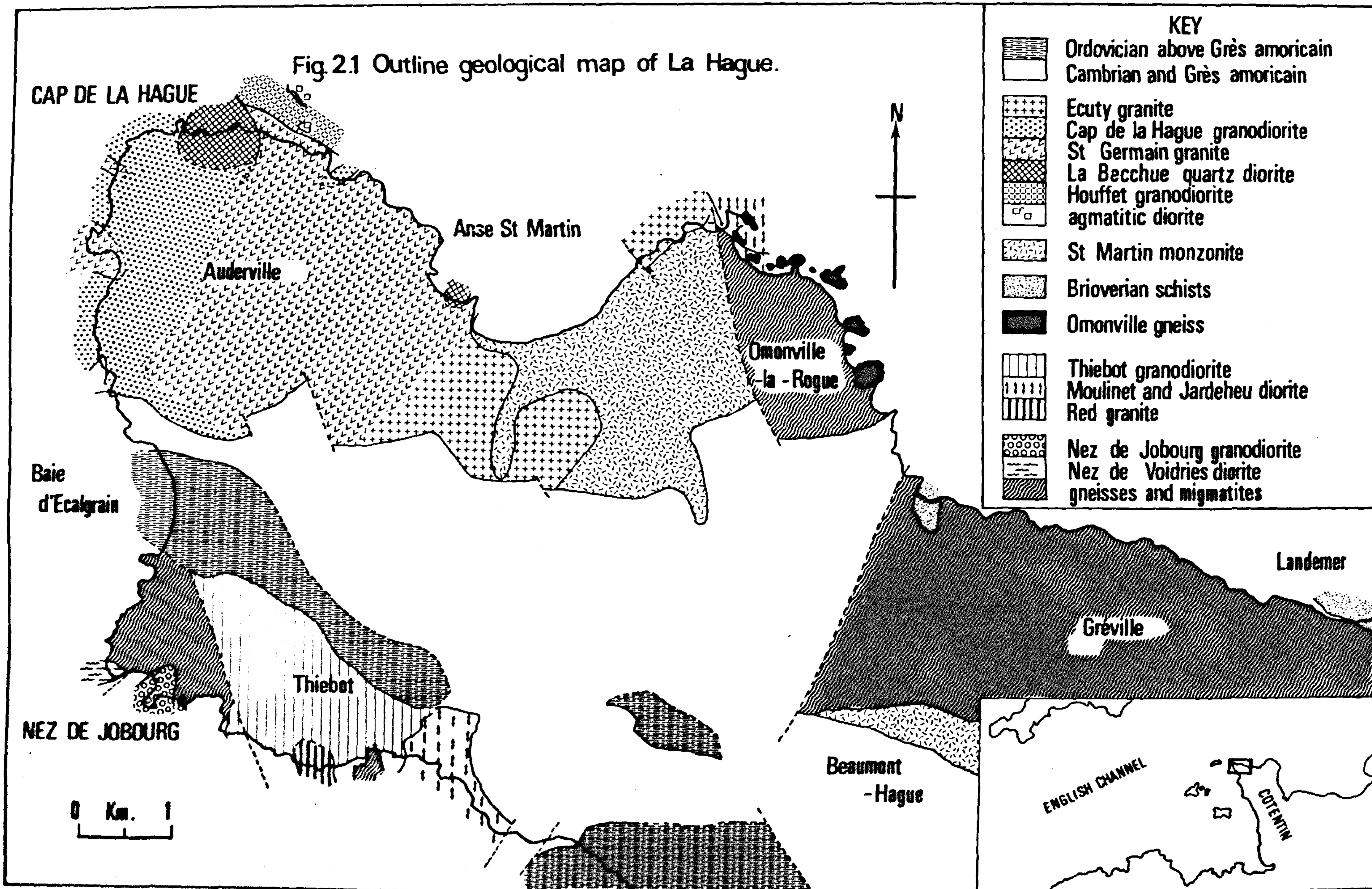


Fig. 2.1 Outline geological map of La Hague.
CAP DE LA HAGUE
Anse St Martin
Auderville
Omonville -la -Rogue
Baie d'Ecalgrain
Thiebot
NEZ DE JOBOURG
Beaumont -Hague
Landemer
Gréville
N
0 Km. 1
KEY
Ordovician above Grès amoricain
Cambrian and Grès amoricain
Ecuty granite
Cap de la Hague granodiorite
St Germain granite
La Becchue quartz diorite
Houffet granodiorite
agmatitic diorite
St Martin monzonite
Brioverian schists
Omonville gneiss
Thiebot granodiorite
Moulinet and Jardeheu diorite
Red granite
Nez de Jobourg granodiorite
Nez de Voidries diorite
gneisses and migmatites
ENGLISH CHANNEL
COTENTIN

TABLE 2.1

SEQUENCE OF EVENTS IN THE GNEISSES OF THE NEZ DE JOBOURG AREA

Event	Evidence
Sedimentation and formation of S_0	Inclusions of semi-pelite and psammite. Biotite gneisses of sedimentary origin, Anse de Pivette.
Basic lavas or dykes	Now boudins, brown hornblende - garnet - plagioclase - quartz.
? Basic dyke intrusion	Now deformed dykes with folded foliation, e.g. Anse de Pivette.
Emplacement of K-feldspar granites,	K-feldspar gneisses with S_1 banding.
D_1 deformation and production of banding, S_1,	Extremely rare relict F_1 folds in semi-pelitic inclusions, Anse du Culeron, Descente des Grottes. Obvious banding, S_1, now transposed parallel to S_2 and forming F_2 fold hinges in all the gneisses.
and metamorphism, M_1, possibly low pressure amphibolite facies.	Relict andalusite in S_1 banding, relict garnet.
Ultrabasic body emplacement	Now zoned ultra basic lenses

TABLE 2.1
(Continued)

SEQUENCE OF EVENTS IN THE GNEISSES OF THE NEZ DE JOBOURG AREA

Event	Evidence
D_2 deformation and production of S_2 foliation and banding and F_2 folds	S_2 now seen as main foliation. F_2 only found as small scale fold hinges folding banding S_1 and lying within S_2. Intersection of S_1 and S_2 forms a strong lineation, L_2.
Migmatisation, late syntectonic, together with intrusion of orthogneisses,	Locally disrupts S_1 Anse du Culeron. Nez de Voidries quartz dioritic gneiss. Nez de Jobourg granodioritic gneiss.
and metamorphism, M_2	Amphibolite facies mineral assemblages sillimanite - garnet - muscovite.
Aplitic veining	Pink aplitic veins cross cut S_2 but folded and foliated by D_3.
? Intrusion of basic dykes	Now deformed dykes discordant to S_2 foliation but foliated.
D_3 deformation producing F_3 folds	Asymmetric small scale folds deform S_2 but no new penetrative foliation formed.
? Intrusion of basic dykes	Now deformed dykes discordant to S_2 foliation but foliated.

TABLE 2.1
(Continued)

SEQUENCE OF EVENTS IN THE GNEISSES OF THE NEZ DE JOBOURG AREA

Event	Evidence
Intrusion of granitic bodies,	Moulinet, Jardeheu quartz dioritic gneiss. Thiebot granodioritic gneiss. Red granitic gneiss. Contacts cross-cut S_2 and truncate a foliated basic dyke.
D_4 deformation	S_4 foliation seen in orthogneisses of Thiebot complex. Probable renewed movement on S_2 Possible tightening of S_3 folds.
? Metamorphism, M_3.	Post-D_2 deformed basic dykes show plagioclase + hornblende. Metamorphism some time post-D_2 to post-D_4.
? Intrusion of composite dykes.	Composite dykes cut S_2, Anse de Pivette, Descente des Grottes.
Intrusion of quartz porphyritic granitic dykes and sheets.	Unfoliated bodies cut S_2, Descente des Grottes, La Côte Soufflée, etc.
Retrogressive metamorphism, M_4.	Development of chlorite, sericite etc. in Thiebot gneisses.

Fold generation:	F_1	F_2	F_3	F_4
Distribution:	Rare. Confined to semi-pelitic inclusions.	Small scale folds only.	Small scale folds.	Single locality.
Surfaces folded:	S_o	S_0, S_1	S_1, S_2	S_1, S_2
Profile:	Now isoclinal.	Isoclinal, detached, attenuated fold limbs.	Asymmetric.	Tight.
Axial surface foliation:	S_1 foliation and gneissose banding.	S_2 foliation. Now main foliation with S_1 transposed parallel to it.	No new penetrative foliation. Possibly schistosity in deformed basic dykes.	S_4 foliation in Thiebot complex. Possibly schistosity in deformed basic dykes.
Axial lineation:	?	Intersection of S_2 and S_1. Usually defined by prominent ribbing on S_2 of gneissose banding. F_2 fold axes.	F_3 fold axes.	Slight mineral elongation.
Attitude:	Axial surfaces folded into alignment with S_2.	Axial surfaces steep, dominantly trend 18° E of N and dip 70° E.	Steep axial surfaces at a small angle to S_2. Majority trend about 20°E of N but considerable variation.	S_4 virtually N-S dips 75-90° dominantly to E.

TABLE 2.1 (Continued) STRUCTURAL STYLES IN THE GNEISSES OF THE NEZ DE JOBOURG AREA

this area. A sedimentary sequence of dominantly semi-pelitic and psammitic composition has been migmatised and suffered polyphase deformation. It now forms a series of quartzo-feldspathic biotite gneisses. These biotite gneisses have been intruded both by ortho-gneisses of various compositions and by basic dykes at several different times during the course of their evolution.

The constituent parts of the gneisses of the Nez de Jobourg area will be described as nearly as possible in the chronological order of their evolution and to facilitate this a summary table of events is given in table 2.1. This will be amplified and justified as far as possible in the descriptions which follow.

The Inclusions In The Gneisses Of The Nez de Jobourg Area

There are numerous inclusions of almost certain sedimentary origin in the gneisses and it is considered likely that the gneisses were largely derived from the sediments of which these inclusions are remnants. The commonest inclusions in the gneisses are semi-pelitic in composition although psammitic lenses also occur. An iron-rich banded rock has been found on La Côte Soufflée (see plate 2.1). Besides metasedimentary inclusions amphibolitic boudins are not uncommon and ultrabasic lenses are found at several localities.

The Psammitic Lenses

The psammitic lenses are found on La Côte Soufflée and in Baie de la Blette Rompue. Those within the gneisses in the Anse de Pivette will be considered in the section that deals with these rocks. One lens on the north side of the foreshore of Baie de la Blette Rompue measured just under a metre in length and about 40 cm in width. The main foliation in the surrounding gneiss is displaced around the lens.

The mineral assemblage of the psammites is quartz + plagioclase +

garnet + biotite + magnetite. Quartz is the principal constituent occurring as irregular grains up to 1 mm in size with lobate margins. Garnet forms large poikiloblastic grains up to 3 or 4 mm in size and including quartz, plagioclase and magnetite. Occasional yellow-brown flakes of biotite are associated with the garnet. Plagioclase is not uncommon as faintly twinned 1 mm anhedral grains of oligoclase composition (An_{16}) with lobate margins.

The Semi-Pelitic Inclusions

These are found throughout the section from Anse du Culeron to Anse de Seninval enclosed in the biotite gneisses. At the back of Anse du Culeron several larger than usual examples occur in the base of the cliff. These reach up to 2 m in length being lens shaped with their long axes parallel to the main foliation. More often the inclusions are small and less than half a metre long. They often have a foliation developed as a result of a parallel alignment of biotite. Sometimes they show compositional banding on a millimetre scale with leucocratic quartz-feldspar bands occurring at intervals. This banding (here termed S_o) is interpreted as being parallel to original bedding in the sediments. If it is not original bedding at least it is the earliest planar structure that has been recognised within the gneisses of the area. The example shown in plate 2.3 is interpreted as showing the early banding folded by the first recorded deformation in the area (D_1) and then subsequently refolded by the second deformation (D_2) giving a Ramsay type 3 interference structure. Other inclusions, for example those in Anse du Culeron, also show evidence of an early banding S_o and probable early folds, (see plate 2.4). In thin section and semi-pelitic inclusions have a mineral assemblage of plagioclase + quartz + biotite + chlorite + magnetite + garnet.

Slight compositional banding of quartz and plagioclase-rich layers and more biotite rich layers is developed. Biotite flakes grow parallel to this banding (S_0) forming a prominent foliation (S_1) which shows evidence of folding but in the samples examined no new mineral growth has developed parallel to the axial surfaces of these folds. As these folds are the result of the second deformation (D_2) it is thought that the mineral assemblage represents conditions during the first deformation. Plagioclase forms equidimensional anhedral grains up to 0.5 mm in size and is albite-oligoclase in composition (An_7 - An_{12}). Quartz is subordinate to plagioclase and usually interstitial. It shows undulose extinction, composite grains and complex boundaries. Biotite is common and is developed along grain boundaries in slightly ragged flakes up to 0.5 mm in size, sometimes altering to chlorite and with α : yellow, β , γ : brown. Garnet is very rare and occurs as isolated round grains.

Iron-Rich Banded Inclusions

On the south side of La Côte Soufflée, above Anse du Culeron, a series of small inclusions of an iron-rich banded rock were found. Plate 2.1 shows the detail of one of these inclusions about 20 cm by 10 cm in size and with fairly angular margins. The prominent more quartz-rich and more iron-rich bands are off-set from the main foliation in the surrounding gneisses. Inclusions of this type were only found at this particular locality.

In thin-section the mineral assemblage of the magnetite rich layer is seen to be magnetite + amphibole + quartz + sericite and muscovite (after plagioclase?). The amphibole forms prismatic crystals growing on the abundant magnetite. It is pleochroic with α : dull yellow, β : pale green and γ : grass green and has an extinction angle $\gamma \wedge c$: 10°. It is optically negative and has a large optic axial angle. It is considered that the mineral is most probably grunerite as the optical properties most closely fit this amphibole, even though grunerite is usually only faintly pleochroic in yellows and often shows polysynthetic twinning which was absent in the mineral studied. Magnetite forms grains 0.1-1 mm in size and some larger grains up to 5 mm and constitutes the major part of the specimen. It is subhedral to anhedral in form and makes up a network of grains with interstitial amphibole. Quartz occurs in minor amounts between the magnetite grains. Larger areas of sericite and muscovite may represent altered plagioclase.

The origin of these inclusions may only be guessed at as they occur so rarely. The most likely source would seem to be some form of early mineralisation possibly associated with the early deformation (D_1).

Amphibolitic Boudins

These are particularly common in Baie de la Blette Rompue but may be found in most of the sections of the biotite gneisses from Anse du Culeron to Descente des Grottes. They usually have a longer axis of a metre or more parallel to the main foliation (S_2) and a shorter axis of about half their length. They commonly show some sort of banding or more leucocratic veining (see plate 2.2), and this is usually discordant to the main (S_2) foliation in the surrounding gneisses. The main foliation is displaced around the amphibolitic boudins. Trains of widely separated boudins may be traced discontinuously for distances up to several hundred metres enclosed within the main (S_2) foliation, for example all along the south side of Baie de la Blette Rompue. The rocks probably represent original basic intrusive sheets or lavas. They must have been emplaced prior to the first deformation as they have a prominent banding and foliation older than the main foliation (S_2). The formation of the boudins took place during the second deformation (D_2) and may have been accentuated by later deformations.

The mineral assemblages of the amphibolitic boudins are hornblende + plagioclase + quartz + magnetite or hornblende + garnet + plagioclase + quartz + magnetite. Often the plagioclase has been completely replaced by sericite, muscovite and epidote.

The rocks are medium grained with some slight compositional banding with more hornblende-rich and more quartz-rich bands. A well developed foliation is formed by alignment of the hornblende prisms. Hornblende is the most abundant mineral and is usually fairly stubby in shape. It shows pleochroism in brown with α : pale straw, β : light brown and γ : brown or olive green. The optic axial angle is large and the extinction angle γ : c is 20°. Blebs of quartz may be included in the hornblende and complex relationships between hornblende and plagioclase are common. The hornblende also forms needles and blebs, apparently replacing plagioclase, and encloses areas of sericite and epidote which may represent altered plagioclase.

Plagioclase is usually extensively altered and this makes determination of composition difficult. In the few examples where the composition could be estimated it was labradorite (An_{60}). As already stated, needles of hornblende often surround the plagioclase grains and grow into them whilst the central area may be occupied by garnet. In other samples, all the plagioclase has been replaced or remnant grains are anhedral and have an almost skeletal appearance. Garnet is not always present, but often forms small (less than 0.5 mm) subhedral grains either singly or in aggregates of several grains and surrounded by either hornblende or plagioclase. One specimen from the north side of Baie de la Blette Rompue contains circular areas up to 5 mm in size with large numbers of small (0.1 mm) subhedral garnet grains developed in hornblende or altered plagioclase. Quartz is fairly common, either in smaller grains defining the compositional banding or as larger patches up to 3 mm in size, unevenly distributed throughout the rock and appearing to be a late replacive mineral from its textural relations. Magnetite varies from being virtually absent to relatively abundant. It tends to form bands parallel to the foliation and has an extremely elaborate crystal habit with lacy growths and frilly net-like textures overgrowing hornblende. Some rare biotite replaces hornblende but chlorite is more common and shows a similar replacive relationship to hornblende.

The textural relationships in the amphibolitic boudins are interpreted as showing the virtual complete replacement of an original Ca-rich plagioclase by garnet and some brown hornblende and by epidote, sericite and muscovite. Amphibole has probably completely replaced any original mafic minerals. Quartz formed or introduced at this time helped to define the early (S_1) foliation along with the alignment of the hornblende. Since this time there has been no major growth of new mineral assemblages, the only later minerals being some further replacement of plagioclase, replacement of hornblende by chlorite and possibly also some retrogression of garnet to chlorite.

Ultrabasic Lenses

These are found as inclusions within the biotite gneisses at the headland of La Côte Soufflée, in the cliffs on the south side of Anse du Culeron and at various other localities along the coast to Nez de Voidries. They are usually lens shaped and vary in size from

10 cm to about 3 m in length and from 5 cm to about 2 m in thickness. The long axes of the lenses are usually parallel to the main foliation (S_2) but this is locally displaced around the lenses. Sometimes a crude zonation is observed with a white to pale green central region rich in talc and a bright green actinolitic outer region and rarely a thin rim of chlorite or biotite. This zonation is not often perfectly developed particularly in the larger masses.

In thin-section the zones are rarely monomineralic and usually contain some of all the minerals of the other zones, the relative proportions of the minerals changing depending from which particular zone the specimen was selected. Talc occurs as flakes 1-2 mm in size with a random orientation. Actinolite is pleochroic with α : pale yellow, β : pale yellow - green and γ : light green. The extinction angle γ : c is 12°. Actinolite forms bands of broad laths 2-3 mm in length throughout the rock. Biotite laths about 1 mm in length and pleochroic, α : pale yellow, β, γ : light brown, grow across the actinolite. Areas of sericite and other fine grained minerals form bands between the actinolite and it is considered that these, from their habit, may represent extremely altered plagioclase. No examples of less altered original ultrabasic material were found.

Examples of this type of zoned ultrabasic body have been described elsewhere, for example Read (1934) gave detailed descriptions of occurrences on Unst and these have been made the subject of a subsequent chemical study by Curtis and Brown (1969, 1971); Sutton and Watson (1957) described similar occurrences from Sark. There is no reason to suppose that the zoning in the examples from La Hague has evolved in a different manner from that proposed for the other occurrences. That is by metasomatic transfer between rocks of very different composition, during a period of regional metamorphism. There is insufficient evidence to define exactly when this took place. It is suggested that the most reasonable explanation is that the original ultrabasic material was emplaced either prior to or during the first deformation and was boudinaged and then zoned during the second deformation and metamorphism.

<u>The K-Feldspar Gneisses</u>

The K-feldspar gneisses are found in the centre of Anse du Culeron, the back of Baie de la Blette Rompue and along the section north of Descente des Grottes (see end map 3). They appear greenish in colour and have a discontinuous banding formed by quartz and feldspar bands edged with slight concentrations of biotite. Within this banding K-feldspar megacrysts up to several centimetres long occur sporadically. These do not normally appear to post-date the banding (see plate 2.5). In some cases the banding is more continuous and small scale folding of the banding is seen.

Within these gneisses the banding corresponds to the S_1 foliation elsewhere and it is now generally transposed parallel to the S_2 foliation. Both D_2 and D_3 structures may be seen. However, because of the discontinuous nature of the banding, these structures are not readily apparent. The gneisses are cut by discordant, pink quartz-feldspar veins which are deformed by the D_3 folds and have a faint foliation developed in them. They are either pre- or syn- the D_3 deformation.

The contacts between the K-feldspar gneisses and the biotite gneisses are usually concordant with the main foliation (S_2) but may sometimes be slightly discordant. Although it is possible to readily differentiate between these rock-types it is difficult to observe the exact point at which one ends and the other begins as they seem to merge into each other over a distance of centimetres at the contact.

In thin section the K-feldspar gneisses show the mineral assemblage, plagioclase + quartz + K-feldspar + biotite + magnetite + chlorite. Garnet may sometimes be present as may be epidote and clinozoisite. Apatite and zircon occur as accessory minerals. The gneisses are medium grained with a granitic texture and composition. They have a banding and foliation which is variably developed. The foliation is formed by compositional bands of areas that are more quartz-rich and contain K-feldspar megacrysts and of areas that are more biotite-rich. It is also emphasised by the alignment of biotite, preferred orientation of quartz grains and by the slight augen shape of some of the feldspars. Incipient cataclastic textures, particularly in K-feldspar, are common.

Plagioclase is equidimensional to anhedral and often less than 1 mm in grain size. It has irregular to lobate margins and contains inclusions of quartz and often tends to be surrounded by quartz. It is poorly twinned and is sodic oligoclase (An_{12}) in composition. Quartz grains are 0.1 to 0.3 mm in size and occur in bands and in patches of several grains which have been strained and show dimensional orientation. Some patches appear to have been recrystallised and have simpler boundaries.

K-feldspar is nearly always present but is variable in amount from about 10% to about 40%. It is usually 1 to 2 mm in grain size but may be up to 2 cm and forms rounded grains, sometimes slightly elongate or augen shaped. In some specimens K-feldspar may be seen to be replacing plagioclase, particularly along grain boundaries, and it includes remnant patches of plagioclase and blebs of quartz. The grain boundaries are complex, often partly enclosing the surrounding mineral grains and occasionally with myremekitic growths. Perthite is either poorly developed on a very fine scale or completely lacking. Cross-hatch twinning is faintly seen in some grains. The larger grains often show variable extinction from centre to margin. Undulose and patchy extinction is also common. The grains are strained, micro-faulted and sometimes veined. Zones of myrmekite parallel to the foliation may be seen passing through some of the larger grains.

Biotite is variable in abundance and habit. Normally fine grained (0.1 - 0.3 mm) and pleochroic with α : yellow, β , γ : red-brown, it may be developed parallel to the foliation or as aggregates of flakes associated with magnetite, chlorite and apatite and sometimes with clinozoisite or epidote. Some bands in the rock are much more biotite-rich than others. Biotite-rich margins are formed along some of the quartz - K-feldspar bands. Chlorite occurs intergrown with biotite or as patches, up to 1 mm in size, of small flakes and along plagioclase grain boundaries. Garnet is not always present and when it is found it is as isolated, small (0.1 mm), round grains enclosed in plagioclase or quartz. It may show some retrogression to chlorite.

The K-feldspar gneiss could represent a pre- or syn- D_1 granitic intrusive phase. During the first two deformational episodes any original contacts between it and the biotite gneiss could have been extensively modified. Nothing that might resemble possible granitic veins from the K-feldspar gneiss have been found in the biotite gneiss. Semi-pelitic inclusions in the K-feldspar gneiss north of Descente des Grottes could represent xenoliths. An alternative possibility is that the gneiss represents areas, probably of metasediment, that have undergone potassium metasomatism during the first deformation and the semi-pelitic inclusions are remnants of original sediments. Certainly the thin-section textures suggest mobility of potassium at an early stage in the development of the gneiss. Altogether the present evidence does not permit a definitive solution although further work, on the chemistry of the gneisses for example, might provide a more positive conclusion.

Velde, Quaglieri and Kienast (1971) distinguished a light coloured granite containing garnet in the Anse du Culeron as their "unité 1". This corresponds to the K-feldspar gneiss described here. They also state that this gneiss formed the Nez de Voidries and the tip of the Nez de Jobourg. Although the K-feldspar gneiss does occur north of the Descente des Grottes, the Nez de Voidries headland itself is composed of a distinctive quartz dioritic gneiss which will be described later. No K-feldspar gneiss occurs on any part of the Nez de Jobourg, most of it being composed of a K-feldspar poor granodioritic gneiss which will be shown to be of a later age than the K-feldspar gneiss.

At the headland of La Côte Soufflée a medium to coarse grained gneiss is found. It has concordant contacts with the main foliation in the biotite gneisses. It is grey in colour with fine, continuous bands, up to 10 mm wide, of plagioclase in a dark grey quartz and biotite matrix. The plagioclase bands show small scale folds and it is considered that the gneiss may be broadly coeval with the K-feldspar gneiss although it is granodioritic in composition with little K-feldspar.

Thin sections of this granodioritic gneiss show that plagioclase is oligoclase in composition (An_{15}) and occurs in grains with rounded to anhedral outline. Quartz forms thin bands of slightly elongate grains showing undulose extinction and fairly simple boundaries. Biotite is in flakes 0.3 mm in size with a strong preferred orientation and pleochroic formula α : pale yellow, β , γ : dark brown. Apatite and sphene occur as accessory minerals growing along the cleavages of the biotite. K-feldspar is subordinate and either interstitial or replacing plagioclase.

The K-Feldspar Augen Gneisses

On the south coast from Descente de Perréval to Anse du Tas de Pois and again in Anse des Moulinets a K-feldspar augen gneiss is found. It often forms screens up to 50 m thick enclosed in the gneisses of the Thiebot complex. It is an inequigranular medium to coarse grained rock with a good foliation and with prominent pink K-feldspar augen developed in it. The number and size of the augen vary from place to place. Some are almost round with "tails" into the foliation whilst others are more elongate within the foliation. Larger (up to 5 cm long and 1-2 cm wide) and smaller (less than 1 cm) augen may occur together. The foliation often appears to be displaced around the augen. The augen gneiss in places appears to grade without any sharp boundaries into more finely foliated psammitic metasediments. The augen gneiss contains rafts of semi-pelitic material up to 6 m long and these sometimes show traces of an earlier foliation or banding. More basic inclusions and rare ultrabasic inclusions are also found. An intermittent banding in the augen gneiss has been folded giving rise to small scale F_2 fold hinges within the main S_2 foliation and this is responsible for a strong lineation on the S_2 foliation surfaces. F_3 folds are virtually absent although deformed basic dykes younger than the D_2 deformation have been found. Some post-D_2 pink acid veins occur but these are not common.

In thin-section the K-feldspar augen gneisses show a strongly developed foliation with parallel compositional banding on a scale of less than a centimetre formed by layers of quartz, K-feldspar or plagioclase. K-feldspar shows marked evidence of deformation with undulose extinction and recrystallised areas particularly along grain boundaries. Cross-hatch twinning is only faintly developed. There seems little doubt that the K-feldspar pre-dates the main deformation. Plagioclase is augen shaped and is oligoclase in composition (An_{10}). Quartz shows variable dimensional orientation and in some specimens stringers of quartz may be elongated by a ratio of greater than 10 : 1 and wrapped around the feldspars. Biotite is sometimes found but more commonly chlorite with α : pale yellow, β , γ : green and anomalous blue interference colours form thin trails at boundaries between quartz and plagioclase. Muscovite laths may be intergrown with the chlorite.

The augen gneisses were formed prior to the development of the main foliation and it seems possible from the field relations that they could have originated from metasediments during a period of potassium metasomatism. However, it is also possible that they were originally a granitic intrusive phase. Although different in appearance from the K-feldspar gneisses of Anse du Culeron they may both have had a fairly similar origin at broadly the same period of time.

The Biotite Gneisses

This general term is used to describe the quartzo-feldspathic biotite gneisses which constitute the major part of the Nez de Jobourg area. In detail they vary in composition, mineralogy and appearance.

On La Côte Soufflée and in most of Anse de Seninval the main foliation (S_2) in the biotite gneisses is strongly developed and has the more acidic discontinuous banding and lenses of the earlier foliation (S_1) transposed parallel to it. Rarely, as seen at the southern headland of Anse du Culeron, the S_1 acidic banding has been preserved in a more continuous form. The biotite gneiss often has a composite appearance where bands of slightly differing composition and partly transformed inclusions occur. Later veining adds to the complex appearance of the gneiss. In Anse du Culeron pink feldspar with quartz veins cross-cut the main foliation but are deformed by the third deformation (see plate 2.26).

In thin-section the more acidic bands are seen to be composed predominantly of quartz and plagioclase with a coarser grain size than the rest of the rock. Individual grains may be up to 3 mm in size. The plagioclase is oligoclase (An_{10} - An_{17}) with very poorly developed twinning. Plagioclase grains are often entirely surrounded by quartz and appear cracked and broken. The quartz is slightly elongate parallel to the margins of the bands and has sutured grain boundaries. Biotite is sparse and occurs at grain boundaries although the margins of the quartzo-feldspathic bands do show some preferential concentration of biotite.

The material between the more acidic bands is made up of approximately equal proportions of quartz and plagioclase which occur as augen shaped grains usually surrounded by abundant biotite. Plagioclase is of identical composition to that in the more acidic bands. It is poorly twinned but sometimes shows thin albite lamellae. Patchy replacement of plagioclase by K-feldspar is quite common, although K-feldspar is a relatively minor constituent and always less than 10% of the rock. Quartz occurs in fairly equidimensional grains about 1 mm in size with simple grain boundaries. Biotite, α : pale yellow, β , γ : dark brown, shows strong dimensional orientation and grows along grain boundaries. It is sometimes replaced by chlorite. Muscovite is not present in all specimens, but where it does occur it appears to be developed with biotite or cutting across biotite layers at an oblique angle. Some specimens show fine grained aggregates of chlorite and sericite together with abundant blebs of magnetite in the biotite-rich layers. These could be interpreted as "pinitic" aggregates after cordierite but no positive evidence for the former presence of cordierite was found. Rare, isolated grains of euhedral garnet sometimes show quartz "pressure shadows" and biotite appears to be displaced around them. They could pre-date the formation of the main foliation and are not found in the more acidic bands. Fibrolite occurs sporadically through much of the biotite gneiss associated with biotite, but only in minor amounts. Thus the mineral assemblage most commonly found in the biotite gneisses of the Nez de Jobourg area is quartz + plagioclase + biotite ± muscovite ± (garnet) + magnetite ± fibrolite, with chlorite replacing biotite. The relative proportions of the constituent minerals vary principally in the amount of biotite present.

The Sillimanite-Biotite Gneiss

On the south side of Anse du Culeron and around the headland into Baie de la Blette Rompue the biotite gneiss has developed a more complex mineral assemblage. Sillimanite was recognised here by Jérémine (1930) and an assemblage including kyanite, andalusite and sillimanite has been described by Velde, Quaglieri and Kienast (1971).

The sillimanite-biotite gneiss varies in its appearance in the field. In places it grades into a more biotite poor leucocratic quartz and plagioclase rock. In parts of some outcrops, orange weathering leucocratic bands 5-10 mm wide, and with more biotite rich layers of various thicknesses between them, are fairly continuous and may be traced around small scale folds. In other parts, the leucocratic quartz with plagioclase bands may be from 5-20 mm in thickness with lobate margins and may show fairly marked changes in thickness. Biotite rich layers form cuspate bifurcating discontinuous bands usually thin compared with the leucocratic bands. Both these forms are interpreted as being less strongly deformed by the D_2 deformation as the early banding appears to be more fully preserved. The effects of the D_2 deformation may be more clearly seen in other parts of the same outcrops. The leucocratic banding is thinner, and there is a marked tendency for all boundaries between layers to be parallel and for the thickness of the different layers to be much more uniform. The rock has a strongly developed lineation. A progressive change from the less deformed to the more deformed gneiss may be recognised with the leucocratic bands becoming broken and more discontinuous until they form lenses tapering out at either end and drawn out in the foliation. The rock becomes more homogeneous in appearance and biotite shows a much more pronounced alignment.

In thin-section the most usual mineral assemblage is quartz + plagioclase + biotite + muscovite + sillimanite ± fibrolite + garnet. However in some specimens andalusite has been recorded and rather exceptionally kyanite. The rock has a medium grain size and shows a well developed foliation and prominent banding composed of biotite rich areas and quartz with plagioclase areas. The quartz with plagioclase bands contain partly round grains of plagioclase up to 4 mm in size often completely surrounded by quartz and sometimes containing small rounded inclusions of quartz. It is oligoclase (An_{12}) in composition and is usually at least partly altered to sericite.

In several examples of the apparently less deformed quartz with plagioclase bands, elongate grains of andalusite have been found. Some grains exhibit the normal optical properties of andalusite and show a faint pink pleochroism towards their centre (see plate 2.8) but these are rare. More usually, the elongate laths of andalusite do not show straight extinction parallel to their length. They often appear to be made up of several grains (see plate 2.9) with slightly different optic orientations and hence slightly different extinction positions. The elongate laths do not show a single cleavage parallel to their length and often yield an interference figure close to an acute bisectrix figure with a moderate to large optic axial angle and a negative sign. If the mineral is andalusite then α and hence the c-crystallographic axis are not now parallel to the elongation of the laths. In order to establish the identity of the andalusite one rock specimen was cut into thin slices and the quartz with plagioclase bands clipped out. These were then crushed and subjected to heavy liquid separation using bromoform (S.G. 2.91). X-ray diffraction analysis of the portion that sank showed it to be predominantly andalusite with no detectable sillimanite. The unusual optical properties of this andalusite could be explained if it is considered to be a pseudomorph after an original lath shaped mineral.

The andalusite is not common and is only seen in an unaltered condition in some quartz with plagioclase bands in some specimens. Colourless micas are often developed around the margins of the andalusite grains and progressive replacement of andalusite by clay micas and muscovite may be postulated on the evidence of grains showing various stages in this process, from a thin rim of micas, to deeply embayed relict andalusite surrounded by a wide border of micas, to complete mica pseudomorphs (see figure 2.2). However, the process could not have proceeded at a uniform rate throughout the rock as neighbouring grains of andalusite may show very different stages of replacement (figure 2.2A). If andalusite was ever present in the biotite rich layers it is not seen there now although clay-mica aggregates are.

The clay-mica aggregates now show other mineral phases in them. Subhedral granules of garnet are quite common (see plate 2.7) and

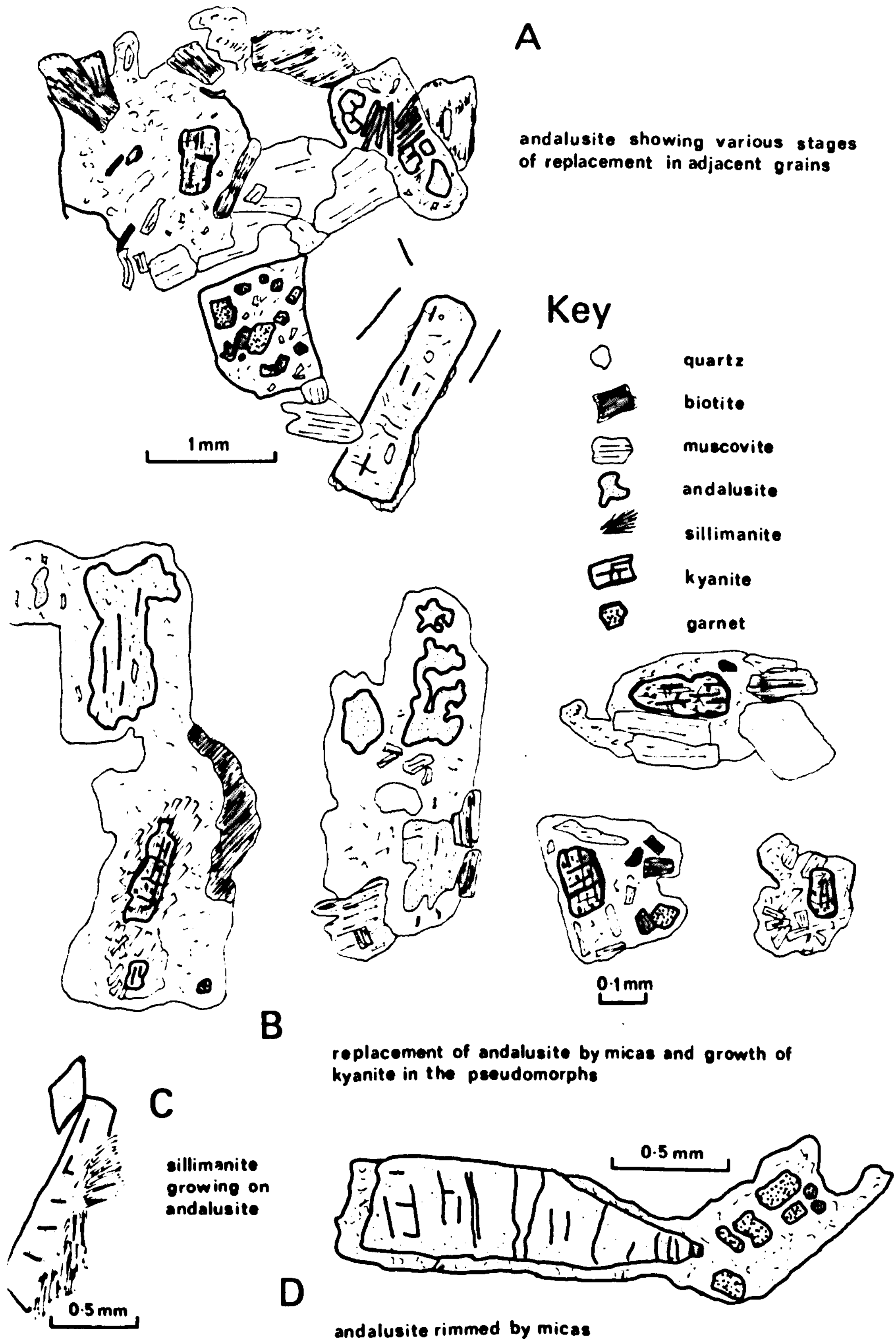


Fig. 2.2 Textural relations in sillimanite gneiss

so are flakes of muscovite and biotite. Kyanite is an extremely rare mineral in the sillimanite-biotite gneiss but when found almost invariably occurs within a mica aggregate. It is suggested that it appears to have grown after the mica aggregate was formed, as the margins of the grains do not appear to show any particular relationship to the boundaries of the mica aggregates, but it is just possible that these aggregates were formed from the break-down of the kyanite (see figure 2.2B).

The biotite rich bands are composed of interlocking laths of deeply coloured biotite in flakes up to 1 mm long. It is pleochroic with α : yellow, β , γ : red-brown and tends to be roughly parallel to the margins of the bands. Some muscovite is intergrown with the biotite. The principal mode of occurrence of sillimanite is closely associated with the biotite. It forms sheafs of slightly radiating laths up to 1 cm long and also broader single prisms (see plate 2.10). More rarely, sheafs of extremely fine needles of sillimanite (fibrolite) occur and these may possibly both pre-date and post-date the development of the more prismatic form. In a few cases it seems there could have been a progressive recrystallisation of earlier fibrolite to form the prismatic sillimanite upon which further fibrolite has grown. Fibrolite may be seen very occasionally growing on andalusite and one example of relict andalusite being replaced by needles of sillimanite has been seen. Sillimanite sometimes forms lath shaped pseudomorphs possibly after andalusite but no andalusite remains. When sillimanite growns in the clay-mica aggregates it is developed with biotite flakes. As already mentioned the main form of sillimanite growth is associated with biotite and all these other forms are unusual or rare.

From the textural evidence cited above andalusite is considered to be the earlier formed polymorph and sillimanite the later. The association of andalusite with the possibly less deformed quartz with plagioclase bands suggests that andalusite may date from the D_1 deformation and the formation of the S_1 foliation and is preserved as a metastable relict phase. Although the lath shaped pseudomorphs could represent an earlier different mineral the simplest explanation would be that these represent the original crystal form of andalusite, and although this andalusite was preserved during the second deformation and metamorphism it was recrystallised giving rise to its present orientation with respect to the crystal outlines.

The replacement of andalusite by very fine grained mica and muscovite could represent a retrogressive phase following the initial formation of andalusite. However an alternative explanation may be offered. Examples of metastable preservation of an earlier aluminium silicate polymorph are not uncommon, for example Nagger and Atherton (1970) describing the contact metamorphism in the aureoles of the Donegal granites stated that sillimanite usually formed independently of pre-existing polymorphs kyanite or andalusite which remained closed systems and that it grew partly from biotite. The marked preference of sillimanite for nucleation and growth on biotite has been discussed in detail by Chinner (1961). The direct replacement of andalusite by fibrolite may require an overstepping of the order of 200°C (Holdaway 1971) and is considered to be an unlikely reaction to occur commonly in nature when other phases such as muscovite are present from which fibrolite may be formed by dehydration with little or no overstepping.

It seems possible therefore that whilst sillimanite grew partly at the expense of biotite the pre-existing andalusite was replaced by micas. This reaction provided additional alumina for sillimanite growth. The breakdown of biotite would provide K, Fe and Mg for the growth of muscovite and of garnet in the clay-mica aggregates at the same time as the growth of sillimanite associated with biotite. Although kyanite may have been an early mineral it is thought that it is more likely to represent a metastable growth at the stage of sillimanite growth stimulated by the particular local conditions present in the clay-mica aggregates. The mineral assemblage of the rock is not an equilibrium assemblage.

Although this proposed scheme of mineral development cannot be proved the evidence does suggest that it is a reasonable possibility. Certainly the textural evidence strongly supports the early development of andalusite before sillimanite. This is in contrast to the sequence suggested by Velde et al. (1971) who proposed kyanite followed by sillimanite and probably late andalusite. This also modifies their possible sequence of pressure and temperature conditions. The possibility that kyanite was a metastable growth makes prediction of pressure and temperature conditions difficult.

<u>The Pelitic Gneiss</u>

On the east side of Anse de Seninval and completely enclosed within the Nez de Jobourg granodioritic gneiss a large raft of pelitic gneiss, some 200 m long, is found (see end map 3). It is variable in composition, some portions being much more pelitic, whilst others are more quartz and plagioclase rich. A prominent compositional banding is developed showing layers of these differing compositions on several scales from less than 10 cm to 40 cm thick. This foliation is locally cross-cut by mainly concordant veins of Nez de Jobourg granodioritic gneiss and both rock types have been deformed by the third deformation which produced abundant small scale F_3 folds.

The more quartz rich parts of the gneiss are medium to fine grained and composed of quartz and plagioclase and relatively sparse flakes of biotite less than 0.1 mm in size developed along grain boundaries. They do not differ much in appearance from some of the more usual biotite gneisses of the Nez de Jobourg area.

The more pelitic parts of the gneiss have the mineral assemblage quartz + biotite + andalusite + muscovite + sillimanite + magnetite, with muscovite usually seen as the principal constituent. The rocks show a well developed banding with more mica-rich layers and fine stringers of quartz. Individual quartz grains are greater than 1 mm long and less than 0.2 mm wide. In the mica-rich layers some biotite, less than 0.1 mm in size and pleochroic with α : pale yellow, β, γ : brown, and more abundant small muscovite flakes grow broadly parallel to the compositional banding, giving rise to the main foliation (S_2). Both micas may include granules of magnetite.

Within this foliation, in some areas rich in muscovite and where the foliation has not been so strongly developed, euhedral andalusite grains are found. They are up to 0.5 mm in size with almost square cross-sections. Although some grains have been completely altered to muscovite aggregates, sufficient grains are preserved to unambiguously determine their optical properties. Small muscovite and biotite flakes may be seen replacing the margins of the andalusite grains and growing around them (see figure 2.3). Subsequent to this, larger muscovite flakes up to 6 mm long have developed and sometimes include andalusite pseudomorphs within them. The large muscovite flakes are parallel to the main foliation and enclose trains of quartz within them. The main foliation shows microfolds developed as a result of the third deformation and this has also caused kinks to form in the cleavages of the large muscovite flakes showing that they pre-date the third deformation (see

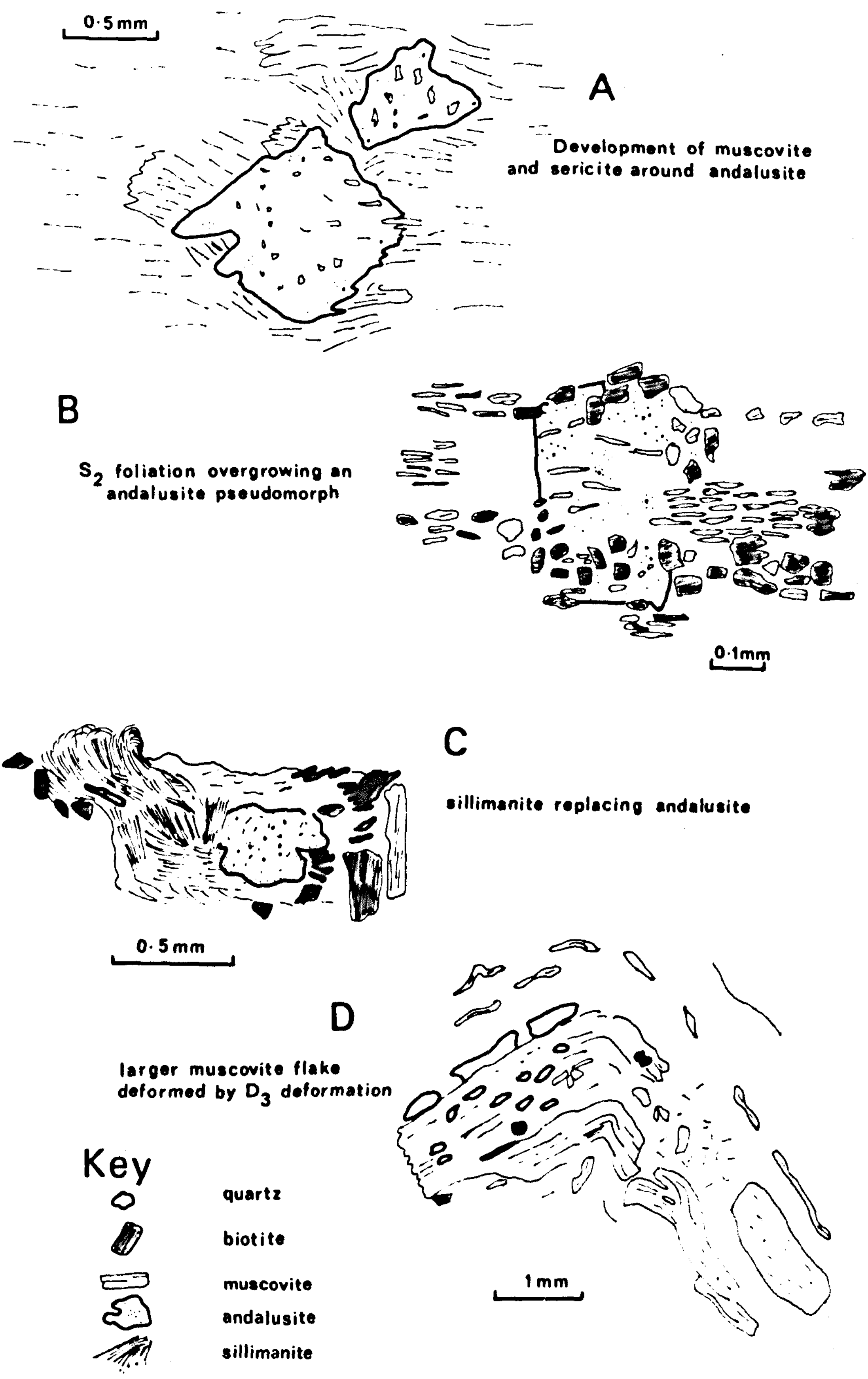


Fig. 2.3 Textural relations in pelitic gneiss

figure 2.3). Fine grained needles of sillimanite are sometimes found replacing andalusite pseudomorphs, but this is a comparatively minor development.

The sequence of events envisaged for the development of these rocks is as follows. Andalusite grew at an early stage and most was destroyed during the development of the main foliation (S_2). It was replaced by muscovite and some biotite. In rare instances sillimanite replaced andalusite during the development of the main foliation. A continued growth of larger muscovite flakes overgrew the main foliation and included stringers of quartz. The main foliation was deformed by a later deformation (D_3) which produced micro-folds in the S_2 foliation and kinks in the larger muscovite flakes. The only new mineral growth at this stage was a very slight recrystallisation and growth of muscovite parallel to the axial surfaces of the F_3 folds.

The Migmatites of Anse de Pivette

The sequence of rocks in Anse de Pivette shows many of the features characteristic of the development of migmatites as a result of local partial melting. In parts of the bay, particularly on the east side, the main body of the rock is a biotite gneiss of sedimentary origin, dark grey colour and fine grained with a lamination picked out by thin lighter bands about 1 mm wide (see plates 2.12 and 2.13) which are now usually parallel to the main foliation. The composition of this part of the rock is semi-pelitic to psammitic and the lamination could have been developed parallel to original bedding. Coarser bands of variable thickness and composed of quartz and plagioclase occur spaced up to 10 cm apart. They vary greatly in thickness from less than 1 cm to become locally 2 or 3 cm thick. They are discontinuous and parallel to the main foliation (see plate 2.12). In rare instances they may be observed to cross-cut small-scale early folds in the lamination (see plate 2.13). Biotite selvedges are developed at the margins of these bands. The bands sometimes take the form of isolated knots and thin ptygmatic veins cross-cutting the main foliation. On the west side of Anse de Pivette lenses up to 10 cm thick of more psammitic material showing early banding may be seen in a much more transformed rock (see plate 2.11). Here, the quartz and plagioclase areas occur as bands, patches and pods with great variations in dimensions from about 2 mm to 4 cm thick and up to 20 cm long. They have biotite-rich margins up to 1 cm thick which merge into each other (see plate 2.11). Occasionally, lenses of a pale medium grained granodiorite are seen within the gneiss (see plate 2.14). The margins of this granodioritic material merge into the surrounding banded rock and wisps of biotite are included in it. In the centre of the bay all gradations between the biotite gneiss sequence and the more homogeneous granodioritic gneiss may be observed. Some areas of biotite gneiss can be seen to have been broken up and progressively replaced by the granodioritic gneiss (see plate 2.15). Veins of the homogeneous granodioritic gneiss up to 5 m wide invade the biotite gneiss. The margins of these veins are broadly concordant with the main foliation (S_2) but do locally cross-cut it (see plate 2.16), suggesting that the development of the veins was at least at a late stage during the main deformation. This is supported by other evidence. Examples of D_2 folds were found in rafts of biotite gneiss included in the granodioritic gneiss veins. Delicate veining was seen to cross-cut other D_2 folds in the biotite gneiss but was itself unfolded. Other thin granodioritic veins showed D_3 folds, and in one case the margin of a thicker granodioritic gneiss vein appeared to have been folded to produce a D_3 fold. Fine grained pink acid veins up to 10 cm wide cross-cut the main foliation

(S_2) and the granodioritic gneiss veins but have been foliated and folded by the third deformation (D_3). Altogether this suggests that the granodioritic gneiss was emplaced towards the end of the second deformational episode and prior to the third deformation.

The mineral assemblage in the more psammitic portions of the biotite gneiss in Anse de Pivette is plagioclase + quartz + biotite + magnetite, and this may be with or without garnet, and with or without chlorite and clinozoisite. Apatite and zircon occur as accessory minerals. These rocks are fine grained with an average grain size of less than 0.5 mm and are predominantly composed of quartz and plagioclase with subsidiary biotite. They often show a compositional banding produced by variations in the relative proportions of quartz and biotite, with bands up to 1 cm wide but often narrower. The banding may have resulted from an original sedimentary variation in composition. Quartz and plagioclase may be elongate and biotite may grow parallel to this banding, producing a foliation which varies from prominent to weak.

Plagioclase is usually about 0.3 mm in grain size. It is often untwinned and may show slight antiperthitic texture. It is albite (An_8) in composition. Quartz may show strong dimensional orientation with a length to width ratio of 3:1 and may form continuous bands up to 1 mm wide. It appears unstrained and has simple boundaries. Biotite forms flakes 0.1 - 0.2 mm in size and is pleochroic with α : yellow, β , γ : brown or green. The green variety of biotite is particularly common. It may be associated with chlorite. Granules of magnetite are included in chlorite and also occur as larger grains up to 0.3 mm in size in trails parallel to the foliation. Clinozoisite occurs associated with biotite. Garnet when present forms subhedral isolated granules sometimes partly retrogressed to chlorite.

On the west side of Anse de Pivette the rocks are more obviously transformed and may have been originally rather more pelitic in composition. They are coarsely banded with more leucocratic quartzo-feldspathic layers with very biotite-rich margins and with dark layers with abundant biotite. The dark layers are equigranular with a grain size of about 0.3 mm and are dominantly composed of quartz surrounded by biotite forming a sagenitic texture and of rare grains of altered plagioclase. Elongate areas 0.5 mm wide of fine grained micas have been partially replaced by foxy-red biotite. At the margins of the leucocratic bands biotite orientated parallel to the layers and with a pleochroic scheme α : yellow, β , γ : brown-black becomes the dominant mineral. Some fine grained muscovite patches are intergrown with the biotite and muscovite flakes 0.3 mm long overgrow the biotite at a high angle to the foliation. Close to the margins of the leucocratic bands fibrolite is sometimes seen growing on the biotite. The leucocratic layers are composed mainly of quartz and plagioclase with some biotite and muscovite growing along grain boundaries. Plagioclase is oligoclase (An_{12}) in composition and is poorly twinned.

In the centre of the bay the granodioritic veins are medium grained inequigranular rocks with dominant plagioclase, quartz in bands and subsidiary K-feldspar and chlorite. Plagioclase is albite - oligoclase in composition (An_8-An_{12}) and forms poorly twinned interlocking grains up to 4 mm in size. K-feldspar is very variable in abundance but never greater than about 15%. It often grows along grain boundaries partly replacing plagioclase or associated with patches of chlorite. Quartz tends to be developed in bands and in some specimens shows dimensional orientation, whilst in others is largely polygonal. Chlorite grows along grain boundaries and is associated with magnetite.

The Nez de Voidries Quartz Dioritic Gneiss

The headland of Nez de Voidries is composed of a quartz dioritic gneiss (see end map 3). It has a fairly well developed foliation which strikes approximately east-west and dips steeply at angles greater than 80°. The northern contact is seen at the bottom of Descente des Grottes where the foliation in the quartz dioritic gneiss is concordant with the foliation in the adjacent biotite gneiss. The quartz dioritic gneiss up to 50 m from this contact shows evidence of a later shearing parallel to the contact. In Anse de Seninval the main contact between the quartz dioritic gneiss and the biotite gneiss is a fault. However at extremely low tides a further contact becomes accessible. Here the foliation in the main body of the quartz dioritic gneiss is discordant to the main foliation in the biotite gneisses but at the contact itself they become concordant. The contact shows alternating bands of quartz dioritic gneiss and biotite gneiss rather than a single sharp junction. A band of quartz dioritic gneiss 1 m wide and parallel to the contact and foliation occurs 0.4 m within the biotite gneiss. This is interpreted as showing that the main foliation in the biotite gneiss was at least formed before the intrusion of the quartz dioritic gneiss and thus allowed easier access of the quartz dioritic gneiss along the foliation. Rafts up to 0.5 m long, often amphibolitic and showing prominent banding, occur within the quartz dioritic gneiss (see plate 2.17) and this again suggests the gneiss is later than the first deformation which was responsible for the production of this banding and could even be later than the second deformation. Deformed basic bodies about 5 m in diameter and more rounded than sheet-like in form occur in the quartz dioritic gneiss in Anse de Seninval. They cross-cut the foliation in the gneiss and also truncate pink quartz and feldspar veins which occur in the gneiss. They have a foliation developed parallel to their margins. At Descente des Grottes an unfoliated quartz porphyry granitic sheet intrudes the quartz dioritic gneiss. Although the field evidence is by no means conclusive it does suggest that the quartz dioritic gneiss was intruded at a late stage during the second deformation. This conclusion is strengthened if the Nez de Jobourg granodioritic gneiss is considered to be closely related to the Nez de Voidries quartz dioritic gneiss, as the field evidence is more convincing at Nez de Jobourg.

The Nez de Voidries quartz dioritic gneiss is a medium to fine grained rock and often shows a planar arrangement of both the light and dark minerals and sometimes a compositional banding with more leucocratic bands parallel to this foliation. It is cut by pink fine grained quartz with feldspar veins which vary in thickness from less than 0.1 m up to 1 m. Some of the thicker ones show a faint foliation. The gneiss is variable in texture and contains small dark xenoliths flattened along the foliation. Small pink feldspar augen are sometimes developed in the gneiss and tend to be more common closer to the pink veins.

Plagioclase is the dominant constituent making up about 50% of the rock and in thin-section it is seen to occur principally as anhedral grains about 1 mm in size but some grains may be up to 4 mm in size. The grains may be augen shaped and surrounded by quartz or chlorite. The plagioclase is often untwinned and altered to sericite. Some of the smaller grains appear quite fresh and unaltered and show thin albite twin lamellae. Both fresh and altered plagioclase is sodic oligoclase (An_{10} - An_{12}) in composition. Quartz grains about 0.2 mm in size often occur in patches up to 2 mm wide which are aligned to give discontinuous quartz-rich bands. Grain boundaries are usually simple with polygonal outlines or are irregular and cuspate.

Hornblende varies in abundance from 10% to about 20% and is pleochroic with α : straw yellow, β : light green and γ : dark green and with extinction angle $\gamma \wedge c = 16\text{-}21^{\circ}$. It is generally anhedral and forms ragged grains of about 1 mm in size with a poikiloblastic texture enclosing blebs of quartz. Any elongation of the grains is usually parallel to the foliation. The hornblende commonly shows alteration to or close association with chlorite. Rarely the hornblende may show relict cores of what once may have been pyroxene. Although there can be no doubt of their presence (see plate 2.18) they are not sufficiently well preserved to determine their optical properties. Hornblende also occurs in aggregates of smaller grains (0.2 mm) with polygonal boundaries and they are probably pseudomorphs, possibly after pyroxene as they occupy rectangular areas up to 2 mm in width. Chlorite is variable in abundance, but is commonly 10% of the rock and is often associated with hornblende. Some flakes may be up to 2 mm in size with inclusions of magnetite and sphene at their margins. Prehnite is sometimes abundantly developed along the cleavage of the chlorite. Biotite is uncommon and is seen as ragged grains up to 1 mm in size. It is pleochroic with α : yellow, β , γ : brown. These flakes are usually altered to chlorite in their outer parts and also along the cleavages. K-feldspar is variable in its abundance and may not be found in some specimens whilst others may contain about 5%. It is usually replacive, forming patches and veins in plagioclase and rims around grain boundaries. It shows variable extinction but no cross-hatch twinning was observed. Fine, impersistent perthite lamellae are irregularly developed in the K-feldspar. Accessory minerals include apatite, zircon, sphene and

TABLE 2.2

MODAL ANALYSES FROM THE NEZ DE VOIDRIES QUARTZ DIORITIC GNEISS

	734	426	417	735	732	733
Quartz	17.9	14.1	11.8	18.4	8.7	15.9
Plagioclase	53.4	52.2	50.3	53.3	56.5	51.7
K-feldspar	6.4	-	0.3	-	0.1	3.1
Hornblende	9.7	14.6	20.3	13.3	23.2	12.8
Biotite	-	-	12.3	2.3	-	0.2
Chlorite	11.9	17.8	4.3	12.1	10.0	12.6
Ore	0.5	1.0	0.6	Trace	0.3	0.3
Prehnite	-	-	Trace	-	1.0	3.5
Apatite	0.2	0.3	Trace	0.6	-	-
Q	23.0	21.3	18.9	25.7	13.3	22.5
P	68.7	78.7	80.6	74.3	86.5	73.1
A	8.2	0	0.5	0	0.2	4.4
F	89.3	100	99.4	100	99.8	94.3
M	22.3	33.7	37.5	28.3	34.5	29.5
Counts	1945	2045	1738	2347	2128	2371

TABLE 2.3

MODAL AND CHEMICAL ANALYSES OF THE NEZ DE JOBOURG GRANODIORITIC GNEISS

	429	503	428		429	503
Quartz	21.8	23.7	21.8	SiO_2	68.1	66.3
Plagioclase	64.2	60.2	63.2	TiO_2	0.32	0.41
K-feldspar	5.7	4.9	6.2	Al_2O_3	16.91	16.03
Hornblende	-	-	-	Fe_2O_3	0.34	0.86
Biotite	1.6	9.2	6.1	FeO	2.13	2.3
Chlorite	6.0	1.1	1.3	MnO	0.04	0.06
Ore	0.6	0.7	1.0	MgO	1.34	1.1
Apatite	0.1	0.2	0.1	CaO	1.78	3.62
Epidote	-	-	0.4	Na_2O	4.95	4.95
Q	23.8	26.7	23.9	K_2O	2.10	1.78
P	70.0	67.8	69.3	P_2O_5	0.12	0.15
A	6.2	5.5	6.8			
F	91.9	92.6	91.1	H_2O	1.4	1.13
M	8.2	11	8.8	Total	99.53	98.68
Counts	2338	2445	2495			

Note: In this and subsequent tables, Q, P and A are the modal proportions of quartz, plagioclase and K-feldspar recalculated to 100%. F is the percentage of the total feldspar that is plagioclase and M is the sum of the mafic constituents.

magnetite.

The field relations of the Nez de Voidries quartz dioritic gneiss show some distinctive features from those of the Moulinet quartz dioritic gneiss, a member of the Thiebot complex which will be described later. The orientation of the foliations in the two gneisses is different, nearly east-west at Nez de Voidries and generally closer to north-south in the Moulinet quartz dioritic gneiss. The Nez de Voidries body has been intruded by basic dykes which have subsequently been deformed whereas no deformed dykes were found in the Moulinet quartz dioritic gneiss. The Nez de Voidries gneiss tends to be finer in grain size. However, to emphasise and reinforce the differences between the two bodies so that there can be no doubt that the Nez de Voidries quartz dioritic gneiss is distinct from the Moulinet quartz dioritic gneiss, several differences in their petrography should be mentioned. The Nez de Voidries gneiss shows more pronounced mineral banding in thin-section. It generally has little biotite compared with the Moulinet gneiss and contains more chlorite. No relict pyroxene has been detected in the Moulinet gneiss. The compositions of their constituent plagioclase are quite different, sodic oligoclase (An_{10} - An_{12}) in the Nez de Voidries and andesine (An_{30} - An_{38}) in the Moulinet gneiss.

At the southern end of Baie d'Ecalgrain a quartz dioritic gneiss, the Ecalgrain gneiss, occurs in contact with the Ordovician sediments. The contact is faulted and the gneiss has been considerably deformed as a result of this later movement. The contact between the quartz dioritic gneiss and the biotite gneiss on the north side of La Côte Soufflée is partly masked by the intrusion of an unfoliated quartz porphyritic granite sheet, but it appears to show a transitional contact with bands of quartz dioritic gneiss within the biotite gneiss.

The quartz dioritic gneiss is foliated and cut by deformed basic sheets. In many ways it appears very similar to the Nez de Voidries quartz dioritic gneiss. The mineralogy of the Ecalgrain gneiss is also very similar to that of the Nez de Voidries gneiss although no relict pyroxenes were found within the hornblende and the effects of a later brittle deformation are very evident. Plagioclase (An_{16}) is often extremely altered and twin lamellae are bent and broken. Grains are traversed by 0.2 mm wide epidote veins. Widely spaced bands of extremely cataclased material cut across the main foliation and some calcite is developed here. Chlorite flakes are bent and prehnite has grown along the cleavages. The minerals formed during this late rather brittle deformation are sericite, chlorite, prehnite, epidote and calcite. If the effects of this deformation are disregarded the quartz dioritic gneiss in Baie d'Ecalgrain may be correlated with reasonable confidence with the Nez de Voidries gneiss on both structural and petrological grounds. It quite definitely cannot be correlated with the gneisses of the Thiebot complex as suggested by Velde, Quaglieri and Kienast (1971).

The Nez de Jobourg Granodioritic Gneiss

The Nez de Jobourg granodioritic gneiss makes up the major part of the Nez de Jobourg and parts of the neighbouring Baie d'Etablette and Anse de Seninval. An off-shoot of the intrusion forms the small headland between Baie d'Etablette and Anse de Pivette.

Approaching the contact between the biotite gneisses and the Nez de Jobourg granodioritic gneiss in Anse de Seninval, the Nez de Jobourg gneiss is first seen as thin veins 2-3 cm wide which weather light orange within the biotite gneiss. They are generally concordant with the main foliation in the biotite gneisses but locally cross-cut it. They have a faint foliation either parallel to the main foliation or slightly oblique to it. The veins have been folded by the D_3 deformation. Closer to the contact the veins become thicker usually being about 0.1 m thick but they also tend to show rapid variations in thickness. The contact of the Nez de Jobourg gneiss is concordant with the main foliation in the biotite gneiss. On the west side of Nez de Jobourg the raft of pelitic gneiss already described shows a well exposed contact with the Nez de Jobourg gneiss in the cliff face at the south-east side of the raft. Here the contact may be seen to locally transgress the main foliation (S_2) in the pelitic gneiss. Small ptygmatic veins of Nez de Jobourg gneiss, parallel with the contact, also cut the main foliation. The Nez de Jobourg gneiss contains inclusions of pelitic gneiss which exhibit the main foliation. The foliation in the Nez de Jobourg gneiss is slightly oblique to the contact. A thin basic dyke cross-cuts the contact and has been deformed as it now shows a penetrative foliation. The foliation in the main body of the Nez de Jobourg gneiss is not well developed and is formed by a slight elongation of the plagioclase and an alignment of the sparse micas. It shows some variation in trend but broadly strikes NNW - SSE and dips at a high angle. Some of the variation in trend may be the result of its modification by the third deformation. The field evidence suggests that the Nez de Jobourg gneiss was emplaced after the initial formation of the main foliation (S_2) but probably before the end of the second deformational episode, as this may have been responsible for the foliation in the veins and the poor foliation in the main body of the gneiss. It was emplaced before the third deformation as this has resulted in the foliated veins being deformed.

In thin-section the Nez de Jobourg granodioritic gneiss is seen to be a medium grained rock composed of an interlocking equigranular mosaic of plagioclase and subsidiary quartz with ragged biotite or chlorite developed along grain boundaries. K-feldspar is only present in subordinate amounts.

Plagioclase makes up about 60% by volume of the rock. It is oligoclase in composition (An_{10} - An_{17}) and forms an anhedral mosaic of grains 3-6 mm in size. Twinning is often only rather faintly seen. Carlsbad, albite and more complex twinning are discontinuous and patchy, sometimes with different areas of the same grain showing twin lamellae with different orientations. Twin lamellae are often diffuse and broad and disappear towards the margin of the grain. Some grains show a distinctive polysynthetic twinning with lamellae up to 0.02 - 0.1 mm wide but thinning out completely and giving rise to a "woven" appearance. In places, there are suggestions of grain growth with globules of quartz enclosed parallel to the margin of the plagioclase. Some large grains enclose smaller grains of plagioclase. K-feldspar is seen replacing plagioclase to a rather limited extent.

Quartz (about 20%) forms patches 3-6 mm in size. Sometimes these are single grains. More commonly, they are made up of grains about 2 mm in size showing undulose extinction. These grains have irregular lobate margins. Some patches are composed of grains less than 1 mm in size with polygonal boundaries. K-feldspar (5%) occurs in interstitial areas as rounded isolated grains 1-2 mm in size and replacing plagioclase. It tends to show very sparse, thin perthitic lamellae and some myremekitic growths at grain boundaries adjacent to plagioclase. The main mafic mineral is biotite, sometimes extensively altered to chlorite. It occurs as ragged flakes 1-2 mm in size with inclusions of magnetite, apatite and sphene. Sometimes aggregates of biotite and chlorite contain rare remnants of altered green hornblende. Chlorite also occurs in fine grained patches with wispy margins developed along grain boundaries and full of very fine grained opaque minerals. Elongate, euhedral crystals of zircon occur as a rare accessory mineral.

The textural evidence, particularly of the plagioclase, suggests a certain amount of recrystallisation either during or following emplacement possibly as a result of deformation.

It has been suggested that the Nez de Voidries quartz dioritic gneiss and the Nez de Jobourg K-feldspar poor granodioritic gneiss were probably emplaced at a late stage during the D_2 deformation. From a consideration of the mineralogical composition of these gneisses it would not seem unreasonable to suggest that they may have been closely related in origin. In fact the migmatites of Anse de Pivette and the Nez de Jobourg and Nez de Voidries gneisses could all be formed by related processes. The Anse de Pivette migmatites would represent partial melting of metasediments and their intrusion by granodioritic veins of local origin whilst the Nez de Jobourg granodioritic gneiss would represent intrusion of a larger body formed as the next stage of the partial melting process and the Nez de Voidries quartz dioritic gneiss intrusion from a lower level of material produced by more advanced partial melting.

The Deformed Basic Dykes

Besides the amphibolitic boudins previously described, which may have originated as basic dykes, other types of deformed basic dykes are not uncommon in the gneisses of the Nez de Jobourg area. It is possible to subdivide these into representatives of several different periods of intrusive activity mainly on the basis of their field relations but also partly on their petrology.

Pre-D_1 Dykes

Several deformed dykes in Anse de Pivette may be interpreted as predating the first deformation. One of these dykes occurs at the rear of the bay towards the east side. It is about 1 m wide and 5 m long. The foliation in most of the body is parallel to the main foliation (S_2) in the enclosing gneiss. The contacts of the dyke are usually concordant to the S_2 foliation in the gneiss but are locally discordant and appear to be partly transposed (see figure 2.4). The dyke contains thin, discontinuous bands of granitic material and also blocks of gneiss showing at least S_1 banding and possibly even S_2 foliation. In the central portion of the dyke a foliation oblique to the dominant foliation in other parts of the dyke has been deformed into small scale fold hinges which have their axial surfaces parallel to the dominant foliation. Rare granitic bands are also folded by these folds.

One sequence of events that could account for the observed field relations would require a pre-D_1 intrusion of the dyke. During the first deformation the dyke was foliated and the granitic fraction was introduced into the dyke parallel to this S_1 foliation. Partial transposition of the dyke margins may have occurred. During the second deformation the strong S_2 foliation in the outer parts of the dyke was produced whilst in the central part the S_1 surfaces were partially preserved but folded with axial planes parallel to the S_2 foliation (see plate 2.21). The dyke margins were transposed parallel to the S_2 foliation and lenses of the gneiss were tectonically included in the dyke. Any later deformations only resulted in faulting and jointing in the dyke. Other explanations of the observed field relations require the introduction of unlikely coincidences. A dyke at the west end and one half way along the east side of Anse de Pivette show similar field relations and folded foliations to those described. (See plate 2.19 and figure 2.4).

These early dykes often have the mineral assemblage hornblende + biotite + quartz + plagioclase + magnetite but this has been

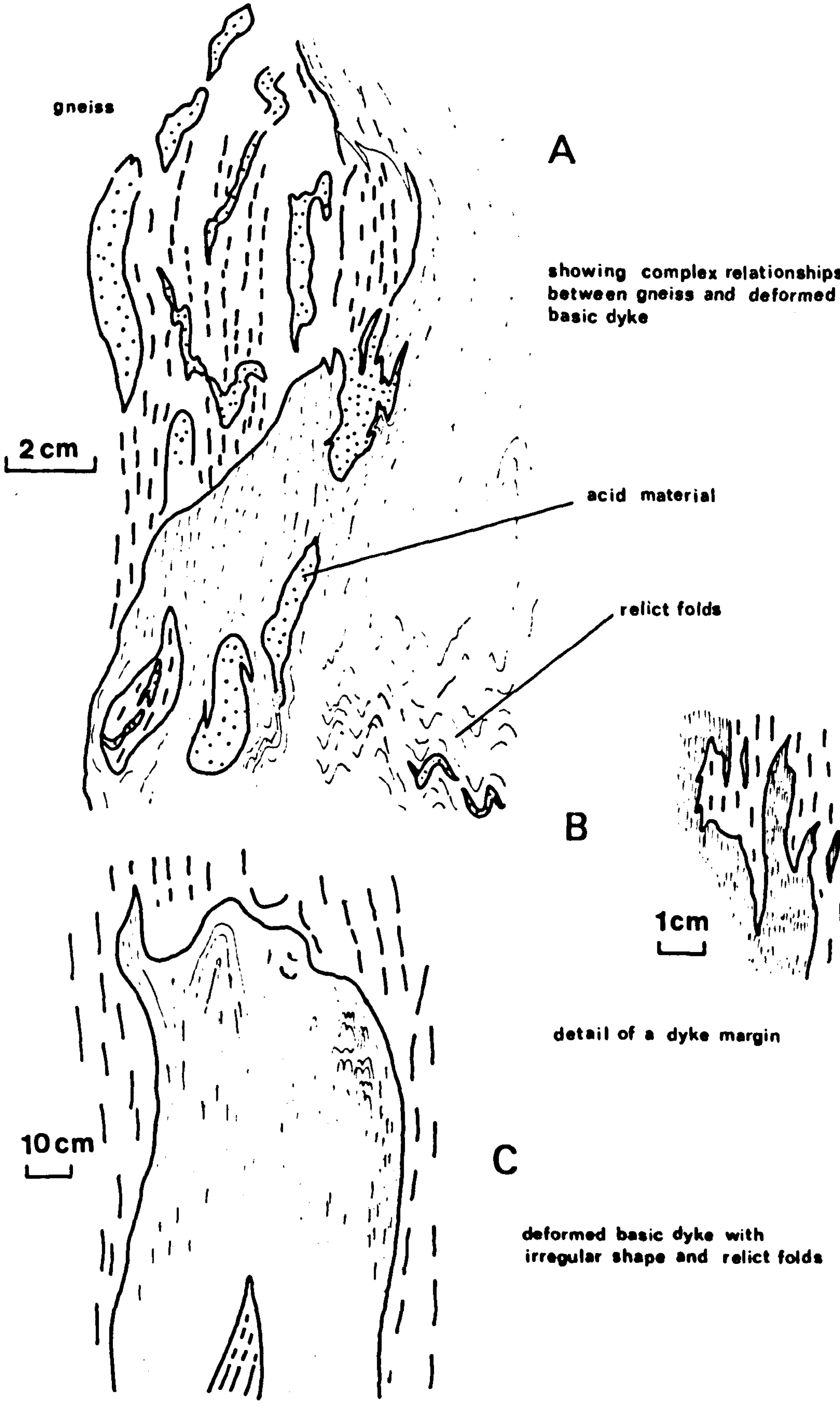


Fig.2.4 Sketches of pre-D_1 basic dykes.

retrogressed in some examples. The rocks are fine grained (0.5-1 mm) and have a prominent foliation consisting of bands up to 1 mm wide of hornblende and biotite alternating with quartz and plagioclase-rich bands. Hornblende, α : pale yellow, β : green, γ : darkish green and extinction angle $\gamma : c = 17^{\circ}$, forms elongate primsmatic grains with ragged terminations and a strong preferred orientation. Biotite, α : golden yellow, β, γ : dark brown, occurs in thin bands often growing around hornblende. Quartz and plagioclase form bands, but most of the plagioclase has been replaced by sericite. Granules of magnetite are fairly common, associated with the mafic minerals and in fine grained patches and bands.

These dykes differ from all the other deformed basic dykes examined in the nature of the foliation and in the presence of biotite and relatively abundant quartz. However, in some specimens nearly all the biotite has been replaced by chlorite and evidence of a later cataclastic brittle deformation may be seen.

Post-D_2, Pre-D_4 Dykes

Many of the deformed dykes are discordant with the S_2 foliation in the gneisses and quite definitely post-date the second deformation (see plate 2.20). One dyke cross-cuts the contact between the Nez de Jobourg granodioritic gneiss and the pelitic gneiss. The dykes are usually less than 1 m wide and cannot often be traced for more than 20 or 30 m along their length, although there are a few thicker more continuous examples. There does not appear to be any evidence to suggest that any of these dykes were emplaced before the third deformation but the possibility that some date from this time cannot be completely ruled out. Deformed dykes in Anse de Culeron and Anse de Pivette both cut through small scale F_3 folds in the gneisses and must be later than the third deformation. The majority of the dykes are likely to have been emplaced prior to the D_4 deformation which was responsible for the foliation in the gneisses of the Thiebot complex because this was the last deformation to affect the area sufficiently to have been likely to be able to produce a penetrative foliation in the dykes. Sheared dykes are found in the Cambrian sediments at Pointe du Houpret but in thin-section these show fairly well preserved igneous textures and some evidence of cataclastic deformation. They would be unlikely to be confused with pre-D_4 dykes if they occurred in the gneisses. One deformed dyke at Pointe du Bec de l'Ane is truncated by the Thiebot gneiss and must have been emplaced before the gneiss (see plate 3.3).

All the dykes have a broadly similar mineral assemblage, hornblende + plagioclase with epidote + chlorite + sericite + magnetite often developed later. However, there may be some variation in texture and grain size. They are usually fine grained with a foliation formed by chlorite and trains of magnetite dust, which is usually abundant. Some show cataclastic textures with augen shaped plagioclase porphyroclasts. Plagioclase is altered to sericite and epidote and a growth of albite (An_9) developed. Hornblende is often almost completely replaced by epidote, magnetite, chlorite and sericite. The mineral assemblage suggests at least upper greenschist facies metamorphism during the D_4 deformation followed by later retrogression.

The deformed dyke truncated by the Thiebot gneiss has a mineral assemblage actinolitic hornblende + albite (An_{10}) + biotite + quartz + magnetite and this may partly result from its proximity to the Thiebot intrusion.

<u>The Composite Dykes</u>

Two examples of composite dykes have been found and both cross-cut the S_2 foliation in the gneisses. One occurs north of Descente des

Grottes. It trends just east of north and is vertical. It is 17 m wide with 1 m thick dark margins. The lighter coloured central phase is intrusive into the marginal phase and contains xenoliths of it. The marginal phase is fine grained (0.1-0.4 mm) and composed of plagioclase + biotite + quartz and pyrite. Plagioclase makes up about 60% of the rock and forms lath shaped crystals with well developed continuous zoning varying from andesine (An_{50}) at the centres to oligoclase (An_{12}) at the margins. The other main mineral is about 30% of biotite, α : pale brown, β , γ : dark brown, in well formed flakes along the plagioclase grain boundaries. Quartz is interstitial and pyrite patchily developed. The central phase is coarser grained (0.2-2 mm) and much lighter in colour. Plagioclase shows a range in size and has irregular shapes and grain boundaries. It is continuously zoned from andesine (An_{40}) at the centres to oligoclase (An_{17}) at the margins. Quartz is more abundant than in the marginal phase and some larger grains are up to 1 mm in size. Sparse biotite is in single ragged flakes.

The other dyke is in Anse de Pivette. It is 6 m wide with the marginal zones each 1 m thick and trends just east of north. In contrast to the dyke at Descente des Grottes the central portion of this dyke is darker but the contact relations indicate that the marginal phase was again the later phase. The centre is very fine grained (less than 0.1 mm) and composed of plagioclase + quartz + biotite + hornblende + magnetite + apatite. It has a well developed foliation formed by alignment of the mafic minerals. Plagioclase is less than 0.1 mm in size but some rare porphyroblastic grains reach 0.3 mm and enclose the other minerals. The mafic minerals are abundant and are hornblende, α : yellow, β : yellow, γ : deep green and biotite, α : golden yellow, β , γ : deep brown or dark green. The lighter coloured marginal phase has a well defined lamination emphasised by the opaque minerals. It contains quartz, plagioclase, hornblende and biotite. It seems likely that both these dykes had a similar origin. Although they are later than the D_2 deformation it is not possible to define the time of their intrusion exactly. The dyke at Descente des Grottes is earlier than an unfoliated porphyritic dyke which cuts the composite dyke and has been chilled against it.

The Quartz Porphyritic Granites

Unfoliated quartz porphyritic granite sheets and dykes have been intruded into the gneisses of the Nez de Jobourg area at several localities (see end map 3). Their precise position in the sequence of events cannot be determined. They are certainly post-D_2 and could well be post-D_4, as suggested later. None of these granites are found cutting the gneisses of the Thiebot complex. The granite is light brown and fine grained with some plagioclase phenocrysts visible. Contacts with the gneisses are generally sharp with the granites exhibiting dark chilled margins.

In thin-section the granites show varying proportions of quartz and plagioclase phenocrysts in a fine grained matrix of quartz and feldspars. Plagioclase phenocrysts (up to 2 mm) are usually euhedral and may show perfectly developed discontinuous zoning. Sometimes they are more rounded or anhedral and may have sericite and epidote growing in them. They are albite (An_7-An_{10}) in composition. Plagioclase also occurs in the groundmass as small (0.1 mm) laths. Quartz phenocrysts (up to 2 mm) are often strikingly euhedral but sometimes show rounding and embayments. The proportion of phenocrysts to groundmass is variable. Some specimens only contain sparse rounded phenocrysts in a very fine groundmass and others are composed

TABLE 2.4

CHEMICAL ANALYSES OF QUARTZ PORPHYRITIC GRANITIC BODIES IN THE GNEISSES OF THE NEZ DE JOBOURG AREA

	419	519	422
SiO_2	70.71	68.83	69.88
TiO_2	0.26	0.46	0.43
Al_2O_3	15.70	15.94	15.65
Fe_2O_3	0.42	1.40	0.85
FeO	1.82	2.30	2.30
MnO	0.03	0.05	0.05
MgO	1.01	0.50	0.57
CaO	1.47	2.47	2.48
Na_2O	5.75	5.21	4.36
K_2O	1.89	2.18	2.40
P_2O_5	0.14	0.19	0.19

All analyses by X.R.F.

419 Porphyritic dyke, N end Descente des Grottes.

519 Quartz porphyritic granitic body, E side of Anse de Pivette.

422 Quartz porphyritic granitic body, Descente des Grottes.

dominantly of phenocrysts with perhaps only 10% of groundmass. The groundmass is made up of an intergrowth of quartz, plagioclase and K-feldspar and varies in grain size from very fine up to about 0.1 mm. Chlorite occurs as flakes (0.1 mm) growing in the groundmass and as euhedral pseudomorphous patches with epidote and ore minerals.

Specimens of the quartz porphyritic sheets in Anse de Pivette (519) and Descente des Grottes (422) were chemically analysed. The results (see table 2.4) show that the rocks are granitic in composition with a fairly high sodium content. Both specimens yielded very similar results and the analysis of a quartz porphyritic dyke (419) from Descente des Grottes was also closely similar to these analyses. On the basis of their similar chemistry and petrography it is concluded that the quartz porphyries all derived from a similar origin and probably at much the same time. In texture they are unlike any other rocks in La Hague and chemically the only rock with a closely similar composition is the Cap de la Hague granodiorite.

Quartz porphyries with apparently identical petrographic features have been recorded on Alderney (Morgan 1957) where they cut the Westerly quartz diorite gneiss and are younger than the Central diorite. Adams (1967) gives an age of not greater than 635 m.y. ($\lambda_{Rb} = 1.39 \times 10^{-11} yr.^{-1}$) for the Alderney quartz porphyries. If the Nez de Jobourg quartz porphyries are of a similar age this would probably make them post-D_4.

The Structural and Metamorphic Evolution of the Nez de Jobourg Area

Having described the main rock types of the Nez de Jobourg area and discussed something of the sequence of events it remains to develop this sequence further and to discuss the relative orientations of the different structures. The relationship of the Thiebot orthogneiss complex to the gneisses of the Nez de Jobourg area is described in detail in Chapter 3 together with those events which affect the rocks of the Thiebot complex (see table 2.1).

The structural evolution of the gneisses of the Nez de Jobourg are together with the Thiebot complex may be described in terms of four deformational events, D_1-D_4, with D_1 the earliest succeeded in order by the others. However, this is not intended to imply anything about the separation of the events on a time scale, for example D_1 and D_2 may have been very closely related in time whilst the age determinations of Leutwein et al. (1973) suggest a large time interval between the formation of the Nez de Jobourg gneisses and the D_4 deformation.

The sequence has been built up by observation of the effects of later deformation on earlier structures. However, large scale folds cannot be traced and refolded folds are rare. The account therefore relies heavily on small scale structures and the effect of these on earlier surfaces.

The earliest structure seen is the banding (S_0) in the semi-pelitic inclusions. It is not possible to say anything about the original extent of its development and orientation as it is now only preserved in isolated fragments. It may represent original bedding or a metamorphic differentiation parallel to bedding. This banding must be earlier than the main foliation (S_2) as it is often completely enclosed by it. Evidence that it is definitely earlier than the S_1 banding is tenuous and is limited to several examples that have been interpreted as F_1 folding of the S_0 banding refolded by F_2 folds (see plate 2.3).

Prior to the formation of the main foliation (S_2), a gneissic banding (S_1) was developed throughout the area and this has been assumed to have taken place during a deformation, D_1. The S_1 banding is now largely transposed parallel to S_2 but may sometimes be seen as strongly attenuated. F_2 fold hinges within the S_2 foliation (see plates 2.22 and 2.23).

The S_2 foliation resulting from the D_2 deformation is developed throughout the gneisses of the Nez de Jobourg area. Its present disposition is shown in figure 2.5 where it may be seen to have a dominant orientation 18°E of N with an inclination of about 70° to the east. Although there is a spread about this direction there is no evidence indicating a major reorientation of the S_2 surface since the time of its formation. In the region of Descente des Grottes and Anse de Seninval there is a deviation from this dominant orientation to one with a strike closer to 65° E of N. This is shown as two subsidiary maxima on figure 2.5, and also in the plots for the sub-areas of figure 2.6 and on end map 3. The foliations in the Nez de Voidries quartz dioritic gneiss and the Nez de Jobourg granodioritic gneiss (figures 2.6 and 2.7) are nearly parallel to the S_2 foliation in the surrounding gneisses, that is broadly E - W and NNW - SSE respectively, and it has been suggested that these developed at a late stage in the D_2 deformation, although they may have been modified by the D_3 deformation.

The intersection of the S_2 foliation with the S_1 gneissose banding has produced a prominent lineation on many S_2 surfaces. It takes the form of a felsic ribbing and also of a mica orientation and is parallel to the fold axes of the F_2 folds. Any variation in the orientation of this lineation could be the result of variation in the orientation of the S_1 surface before the D_2 deformation or because of a later deformation, or both (Ramsay, 1960). The present distribution of L_2 may be explained in terms of both these effects. Figure 2.5 shows that a concentration of readings occurs trending about 35° E of N

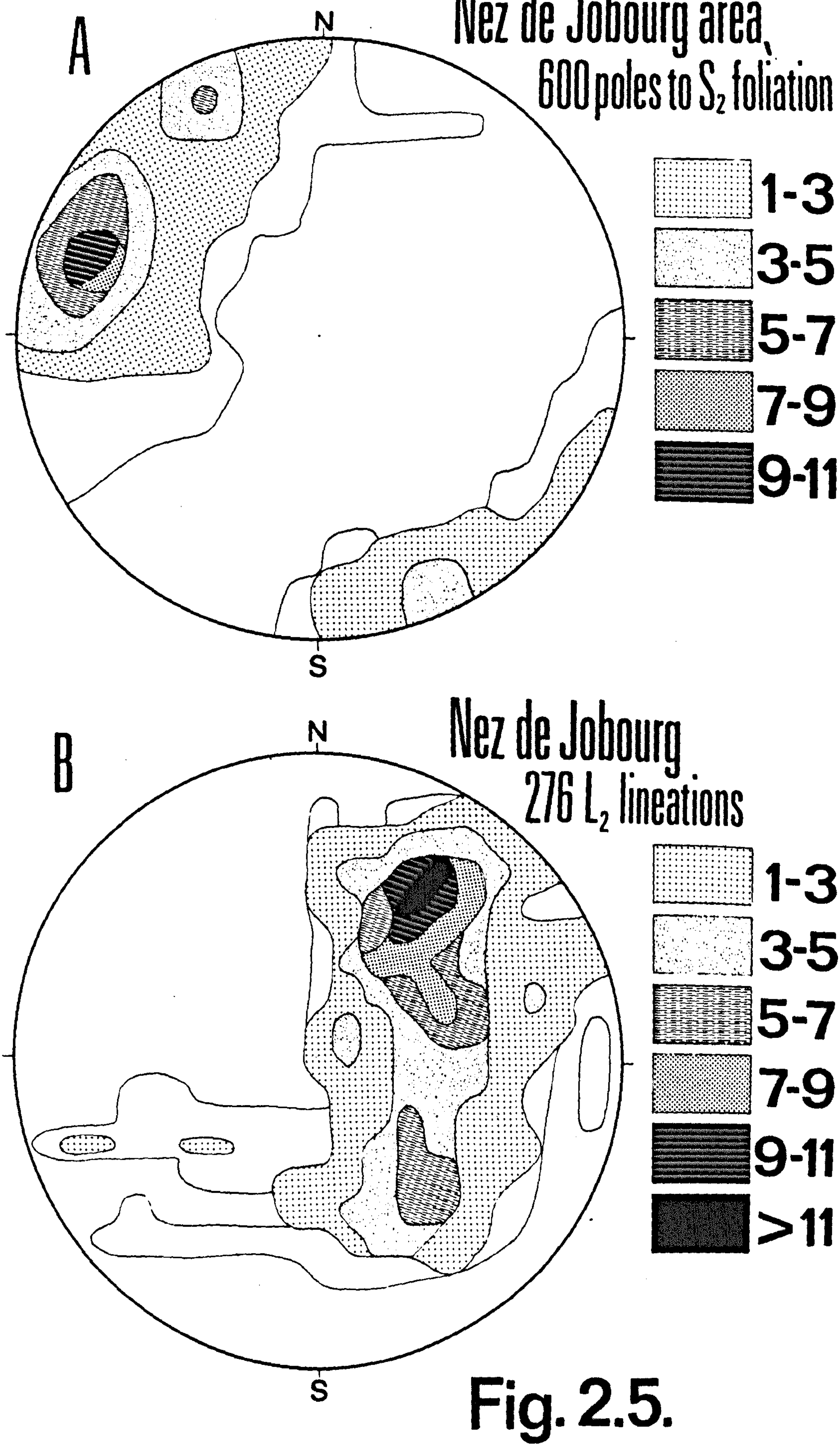

A
N
Nez de Jobourg area,
600 poles to S_2 foliation
1-3
3-5
5-7
7-9
9-11
S
B
N
Nez de Jobourg
276 L_2 lineations
1-3
3-5
5-7
7-9
9-11
>11
S

Fig. 2.5.

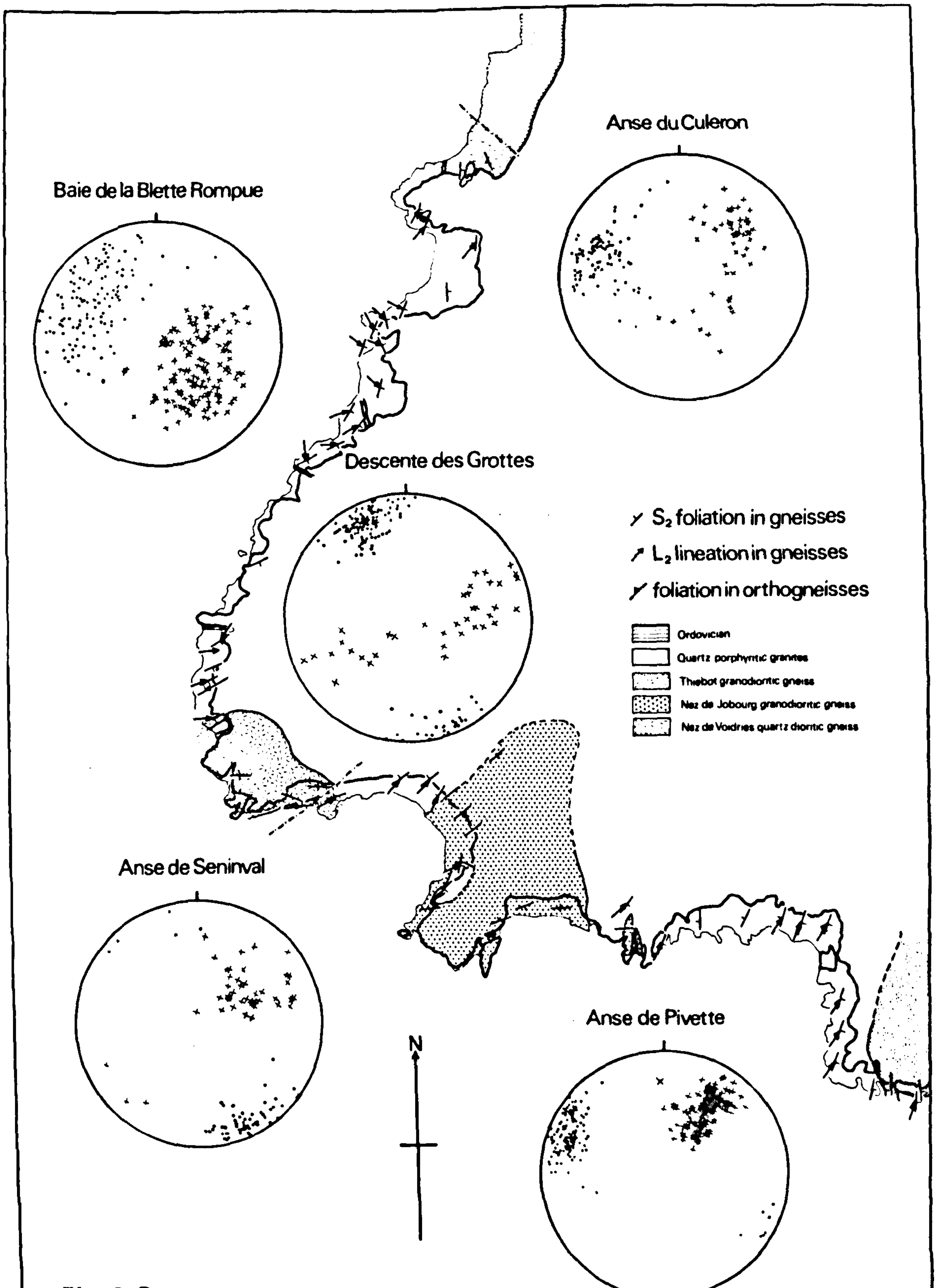


Fig. 2.6 Stereographic plots of S_2 foliation (•) and L_2 lineation (x) for the Nez de Jobourg area.

A

B

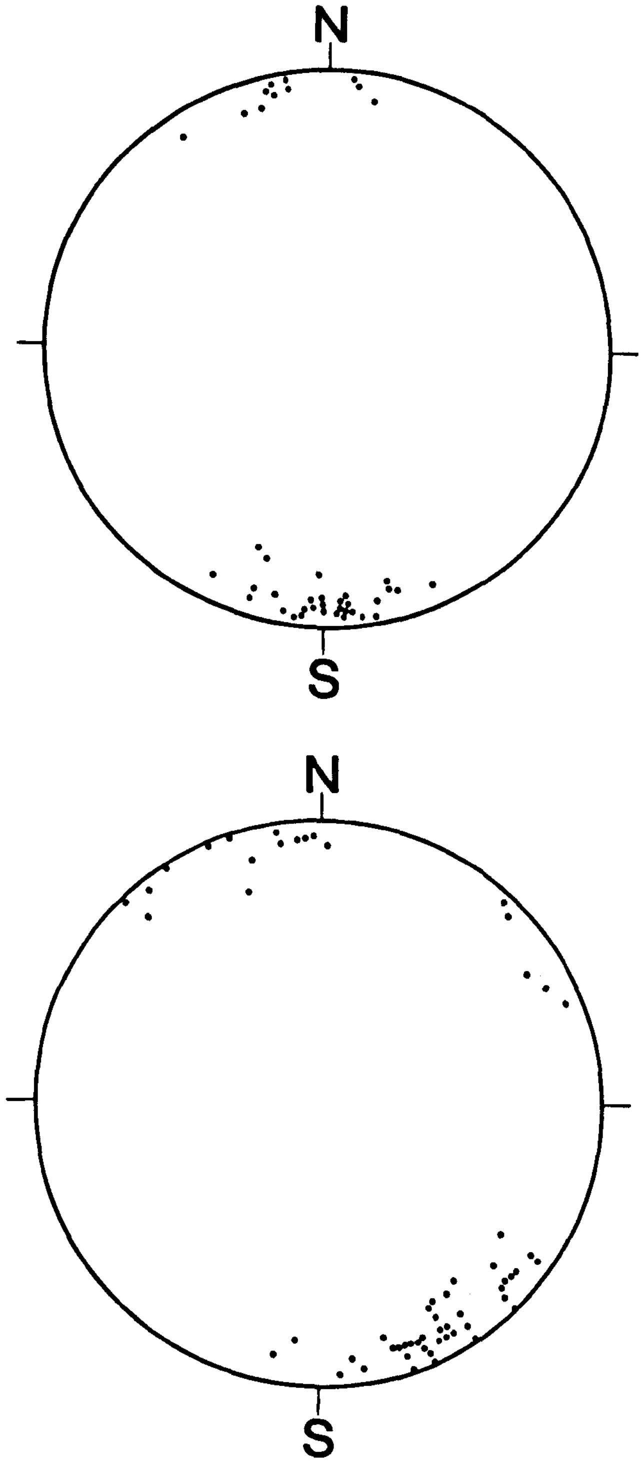


Fig. 2.7

A. Nez de Voidries quartz dioritic gneiss
45 poles to foliation.

B. Nez de Jobourg granodioritic gneiss
60 poles to foliation.

and plunging between 20° and 50° N. Although the attitudes of the S_1 surfaces prior to the development of S_2 cannot be determined, this concentration does suggest that the S_1 surfaces may have had a fairly regular attitude at this time. The effects of later deformation would then be shown by the spread of L_2 from 35° E of N through an arc to plunging between 20° and 50° SE. This is particularly seen in the stereographic plot of the Baie de la Blette Rompue sub-area on figure 2.6, where there is a wide spread of L_2 and a corresponding spread of S_2. This distribution is that which would be obtained for an idealised plot of S_2 and L_2 around a steeply plunging asymmetric F_3 fold. Baie de la Blette Rompue contains several small scale F_3 folds rather than one large one and they have all contributed to the observed distribution. This distribution may be partly enhanced by the S_2 foliation and hence L_2 being deformed around the many basic boudins which occur in this area.

The F_3 folds are usually only seen on a small scale up to about a metre in size. They are asymmetric with one short limb (see plates 2.24 and 2.25) and appear to have formed largely as a result of slip along the S_2 surface. No new axial planar foliation has been formed, apart from locally in a small proportion of the fold hinges. Their axial surfaces are steep and show maxima striking at 16° E of N dipping 80° E and at 28° E of N dipping 80° W as may be seen from the stereographic plot of figure 2.8. The F_3 fold axes generally plunge fairly steeply and trend about 10° E of N. There is, however, a fairly wide spread in the plunge of the F_3 fold axes and this appears to be more marked towards the north of the area. Indeed, in the sub-area plots of figure 2.9 those in the north may show sets of folds with related orientations rather than a single orientation.

The difference in orientation of the S_2 surface in the Descente

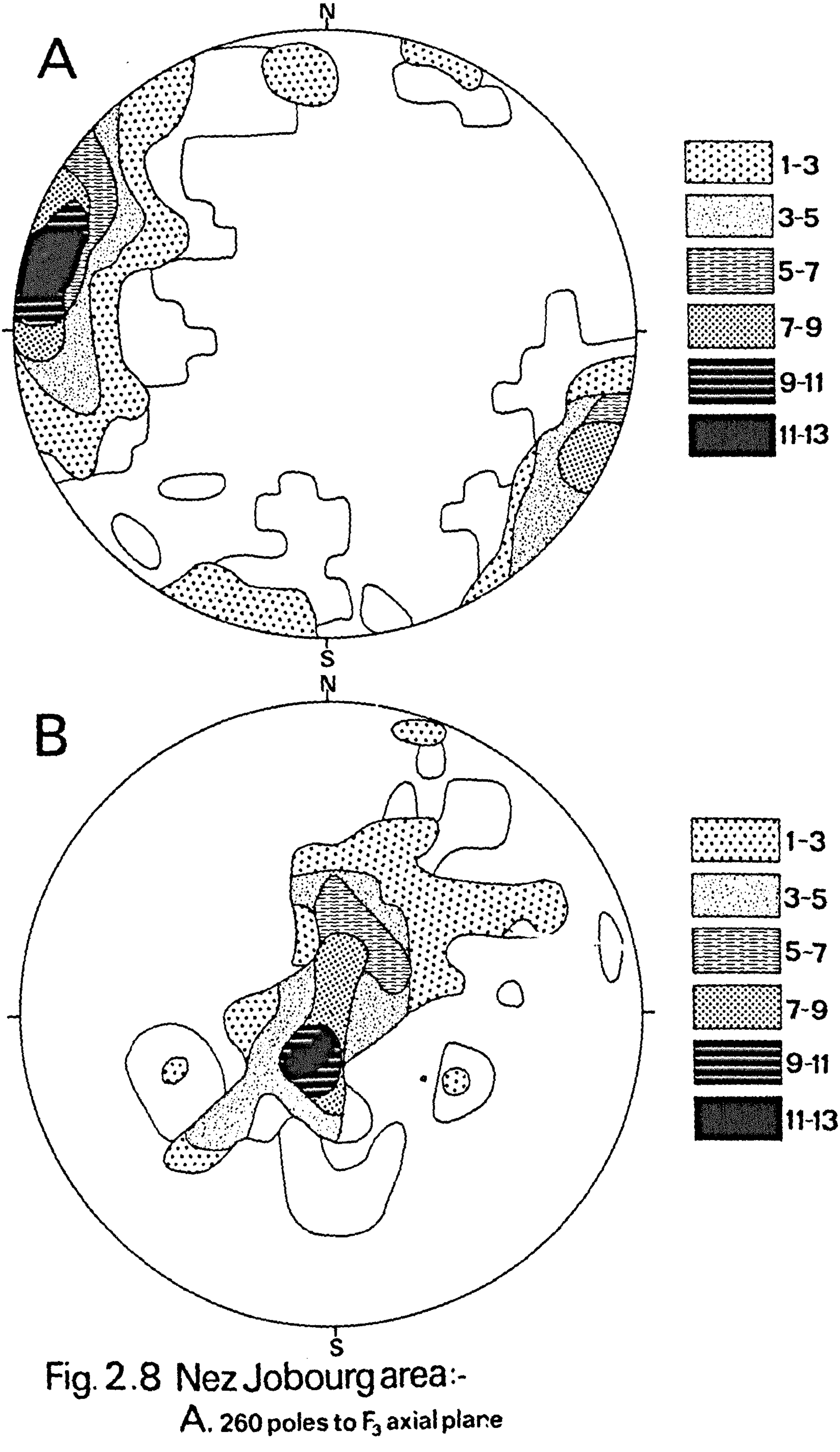


Fig. 2.8 Nez Jobourg area:-

A. 260 poles to F_3 axial plane

B. 120 F_3 fold axes

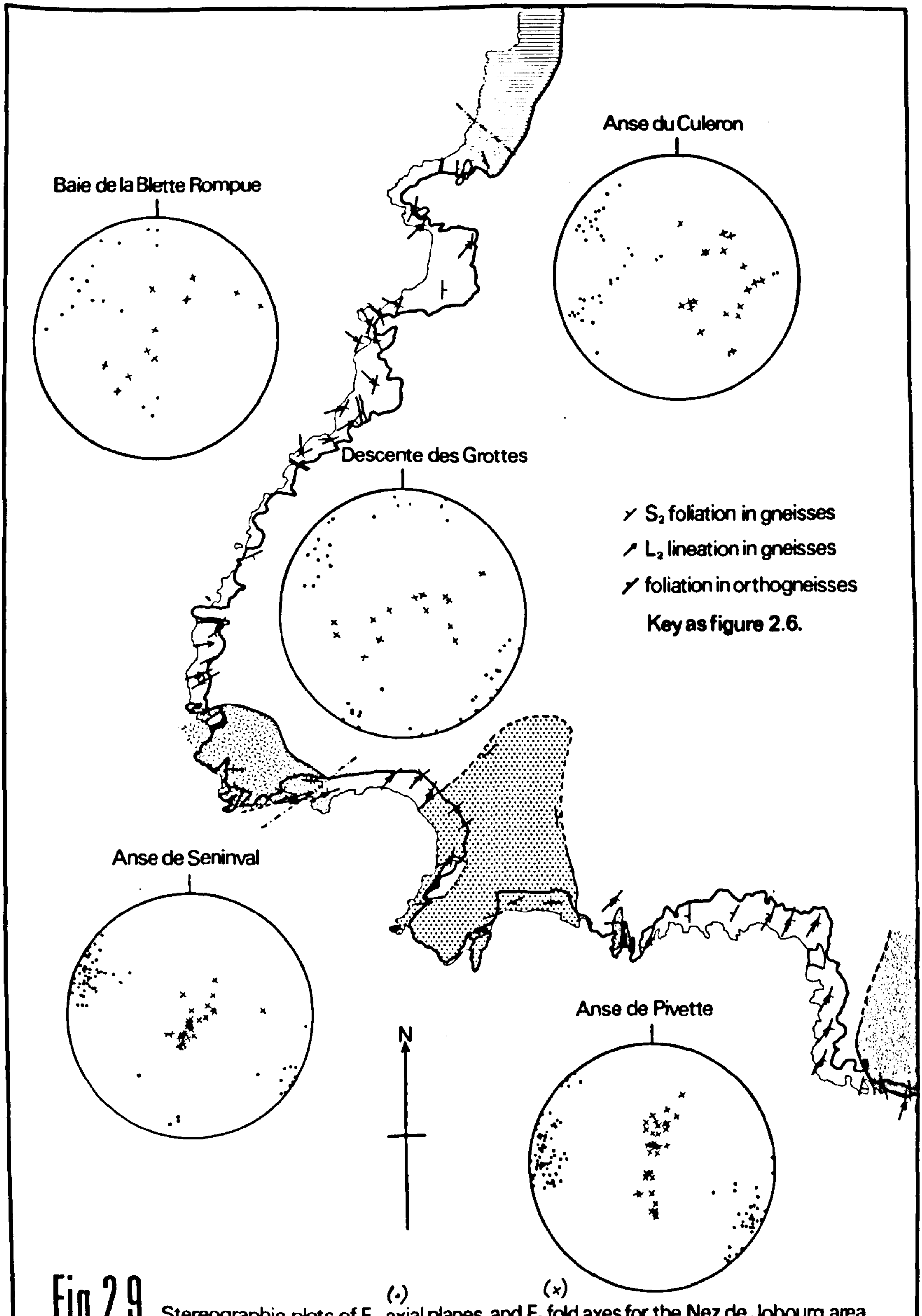


Fig. 2.9 Stereographic plots of F_3 axial planes and F_3 fold axes for the Nez de Jobourg area.

des Grottes and Anse de Seninval region mentioned previously could be part of a larger scale F_3 fold. However, it is not possible to convincingly demonstrate that this must be so from the available data and it is considered more likely that F_3 folds are confined to fairly small scale examples.

No F_3 folds were found in the gneisses of the Nez de Jobourg area east of Anse de Pivette. At Descente de Perréval the gneisses show a uniform N-S trend, but the L_2 lineation on the S_2 surfaces may be seen to plunge either at a moderate angle to the north or at a similar angle to the south. On rare S_2 surfaces the L_2 lineations may be seen to be curved with one end plunging north and the other plunging south. If this is the result of original variation in S_1 it does not appear at all uniform as adjacent S_2 surfaces may show different orientations of L_2. Accordingly, the variation is interpreted as a result of later deformation, either D_3 or D_4 of S_2 in such a way that the L_2 lineations lying on it have been bent without the production of folds (Ramsay, 1960).

The record of the metamorphic history of the Nez de Jobourg gneisses is only partially preserved. Evidence for the first metamorphism M_1 is found in the presence of the prominent S_1 banding which must have been produced during a period of deformation and metamorphism. The relict assemblage in the biotite gneisses which probably consisted of at least quartz + plagioclase + andalusite + biotite gives some indications of possible metamorphic conditions at this time. Other mineral assemblages which may date from this time, although some could be even earlier, include:

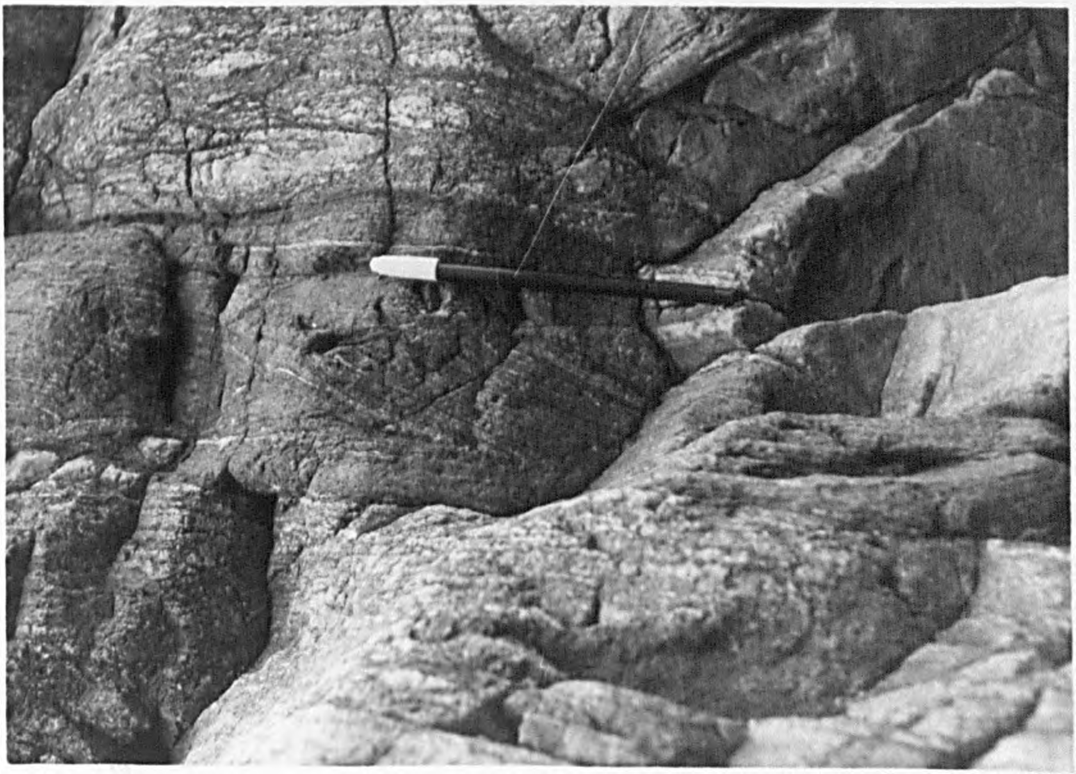
psammite:	quartz + plagioclase + garnet + biotite + magnetite.
semi-pelite:	quartz + plagioclase + garnet + biotite + chlorite + magnetite.

2.1 Iron-rich banded inclusion in biotite gneiss, Anse du Culeron.

2.2 Banded amphibolite inclusion in sillimanite gneiss, La Blette Rompue.

2.3 Refolded fold in semi-pelitic inclusion in biotite gneiss, Descente des Grottes.

2.4 Early fold in semi-pelitic inclusion in biotite gneiss, Anse du Culeron.

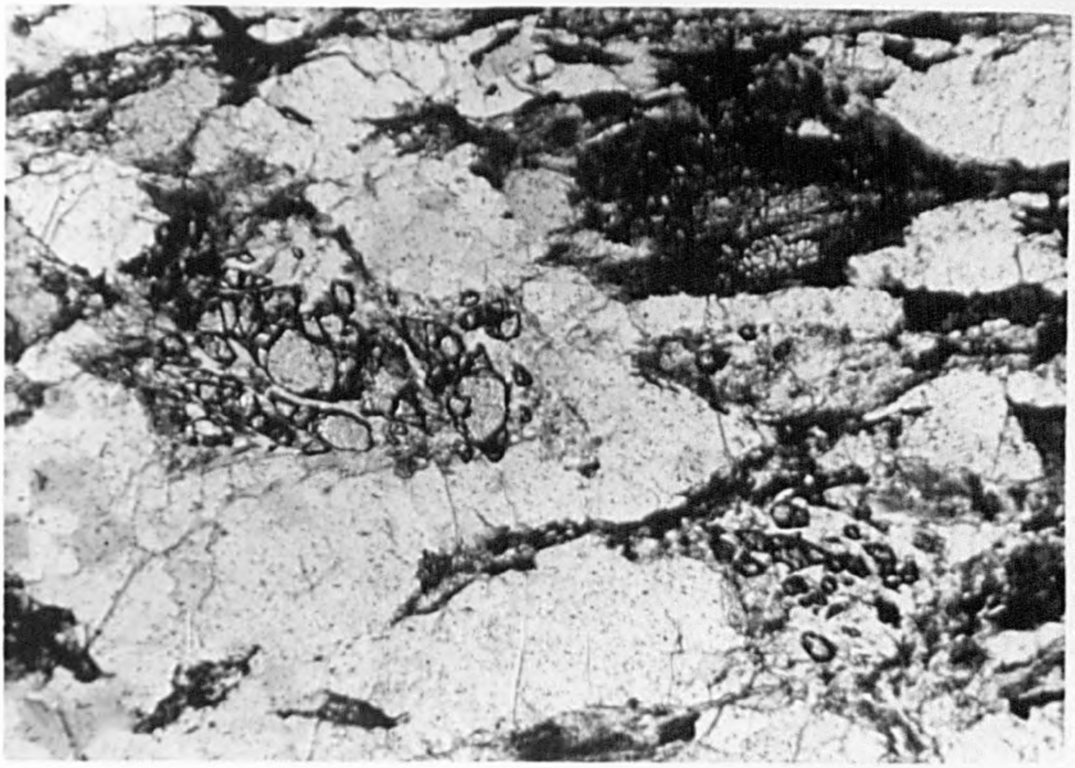


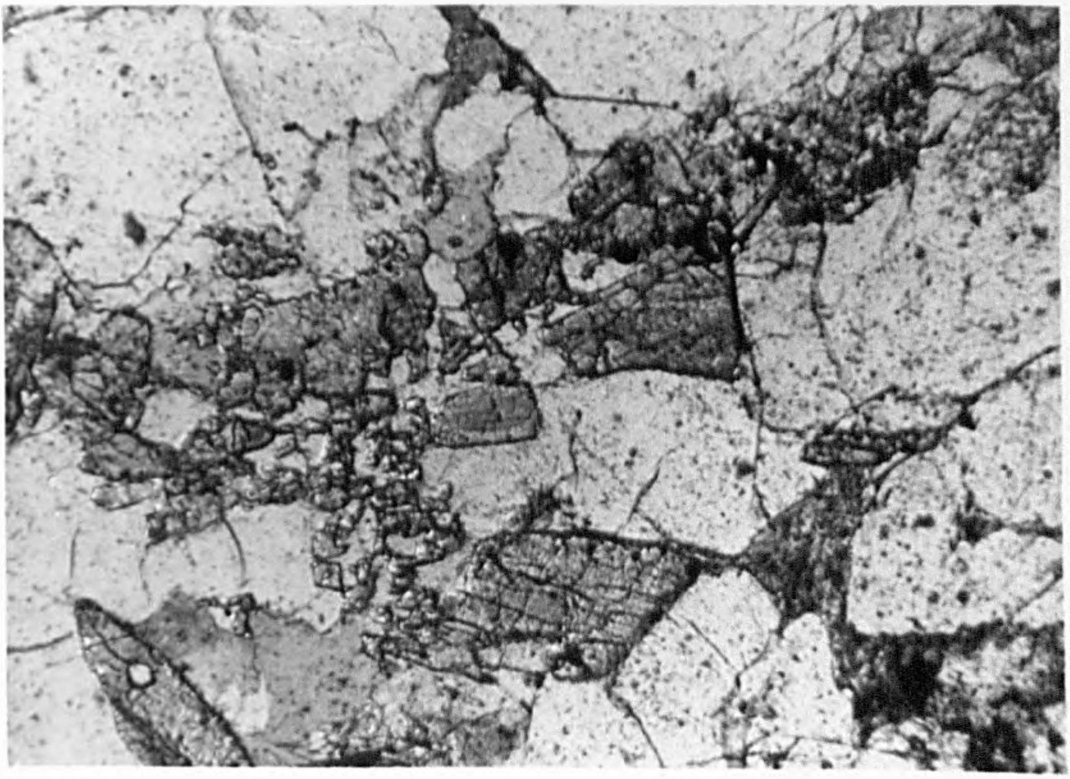
2.5 K-feldspar gneiss, Anse du Culeron.

2.6 Local migmatisation associated with emplacement of Ecalgrain quartz dioritic gneiss, Anse du Culeron.

2.7 Clay mica pseudomorph containing new growth of garnet, sillimanite gneiss. X11.2.

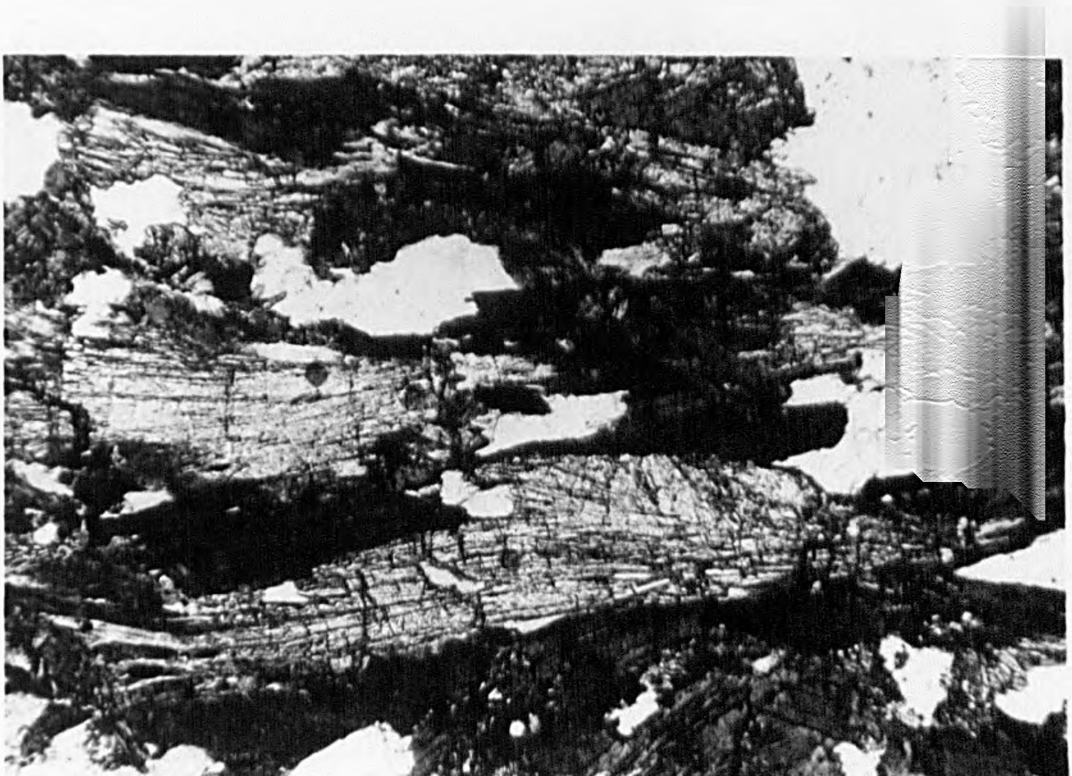
2.8 Andalusite in sillimanite gneiss. Grain at centre shows colour zoning. X11.2.





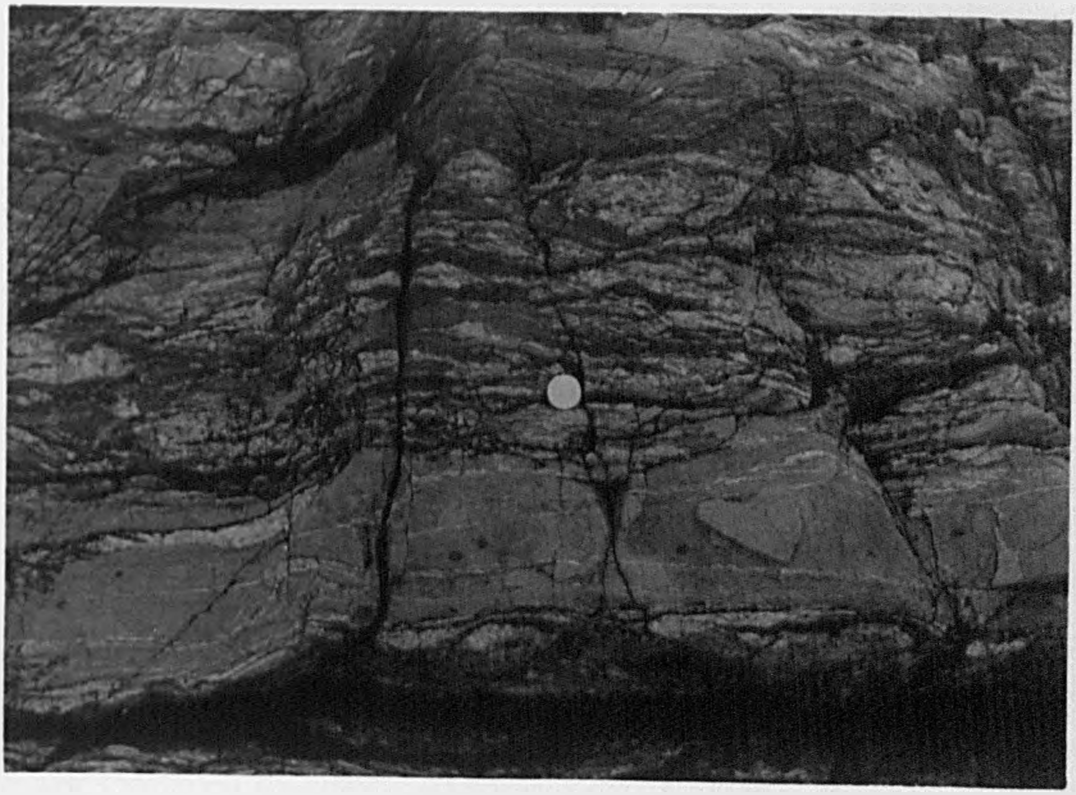
2.9 Andalusite with variation in extinction and rim of clay mica, sillimanite gneiss.
Crossed polars X32.

2.10 Prismatic sillimanite in biotite, sillimanite gneiss. X11.2.



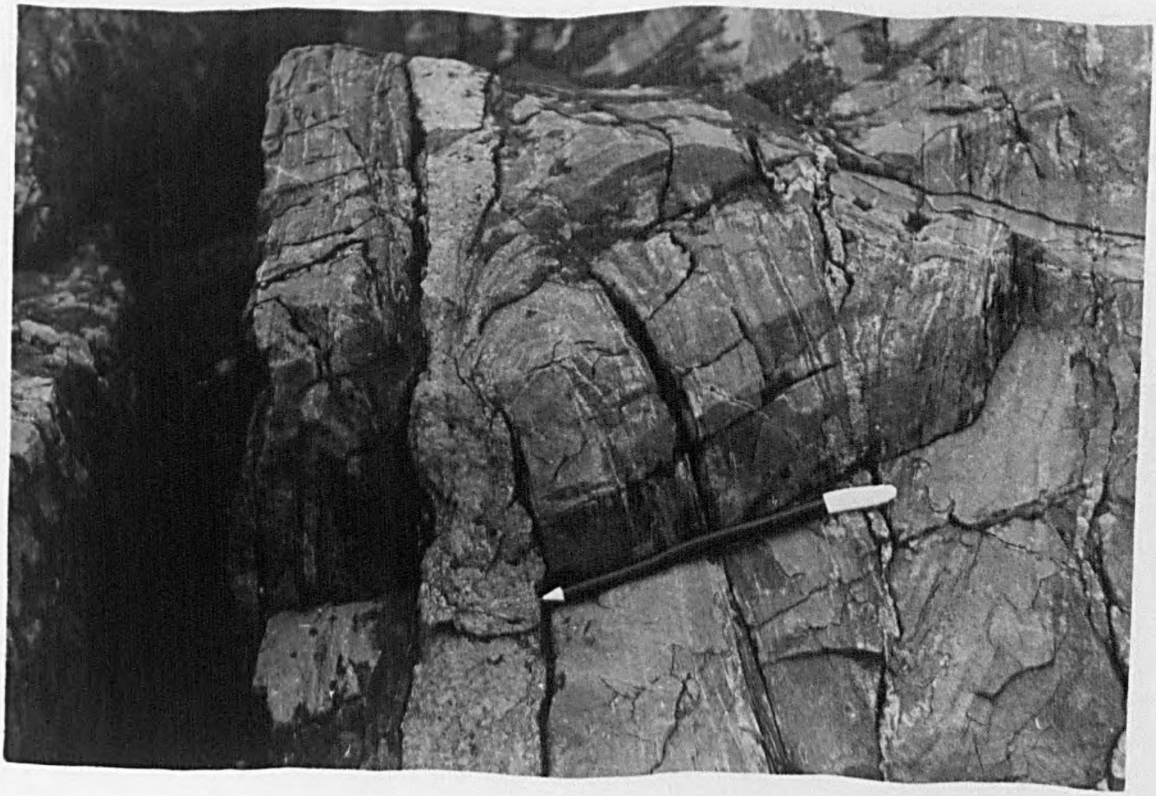
2.11 Preserved early lamination and later migmatisation in biotite gneiss, W side Anse de Pivette.

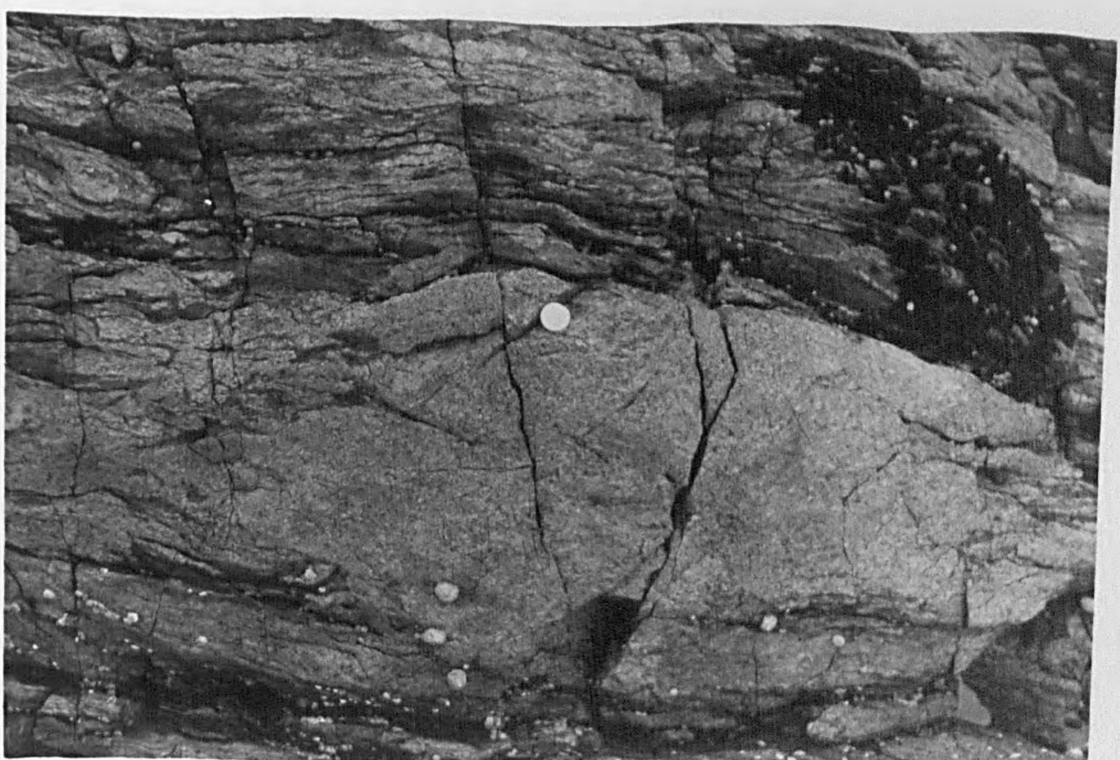
2,12 Composite nature of biotite gneiss, E side Anse de Pivette.



2.13 Early fold cut by D_2 migmatitic material, E side Anse de Pivette.

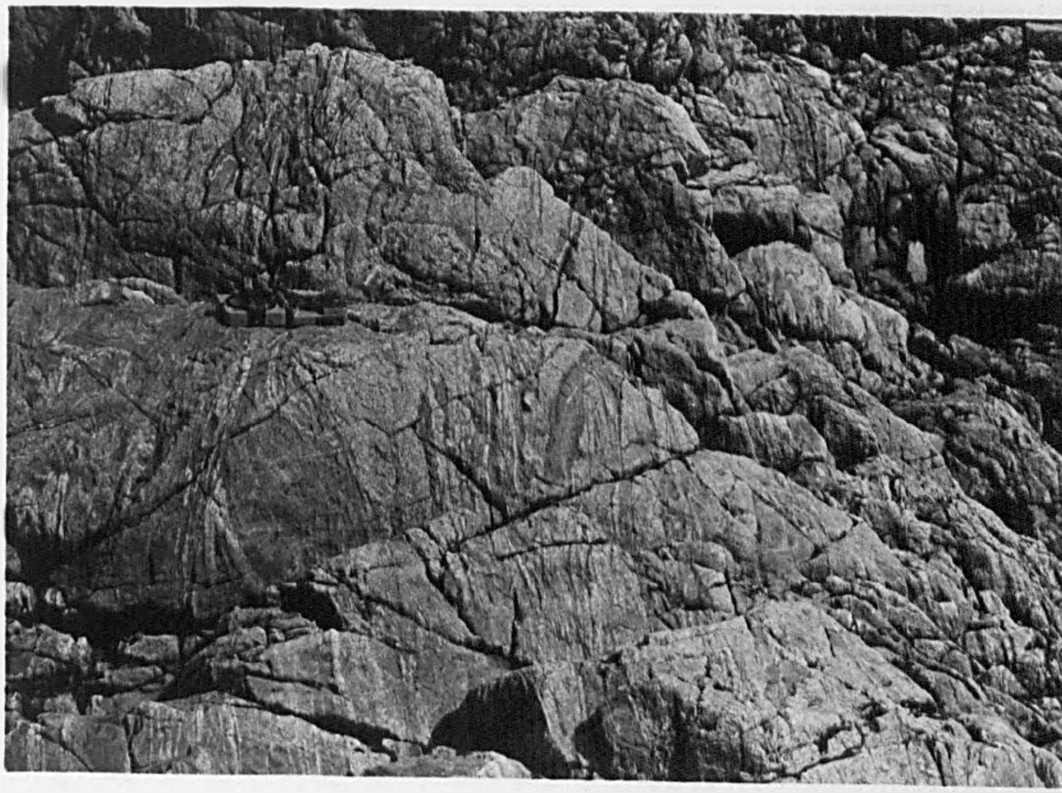
2.14 Granodioritic lens merging with D_2 migmatite, W side Anse de Pivette.

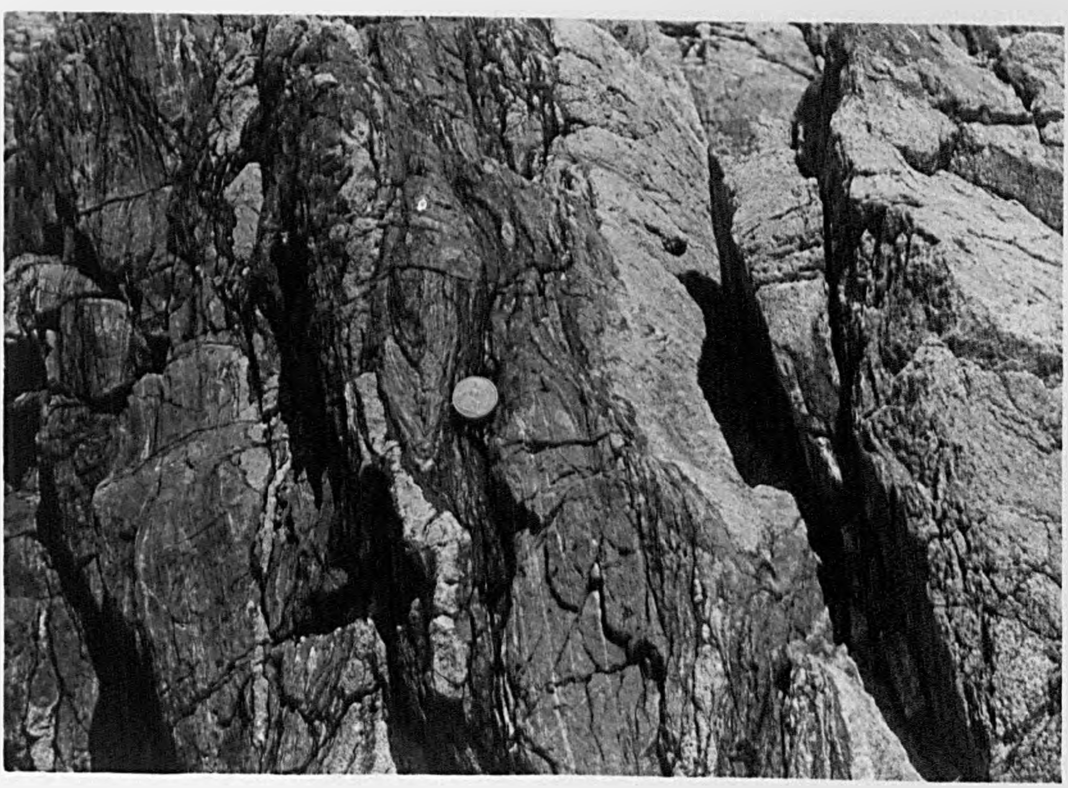




2.15 Replacement of gneiss by late D_2 granodiorite, Centre Anse de Pivette.

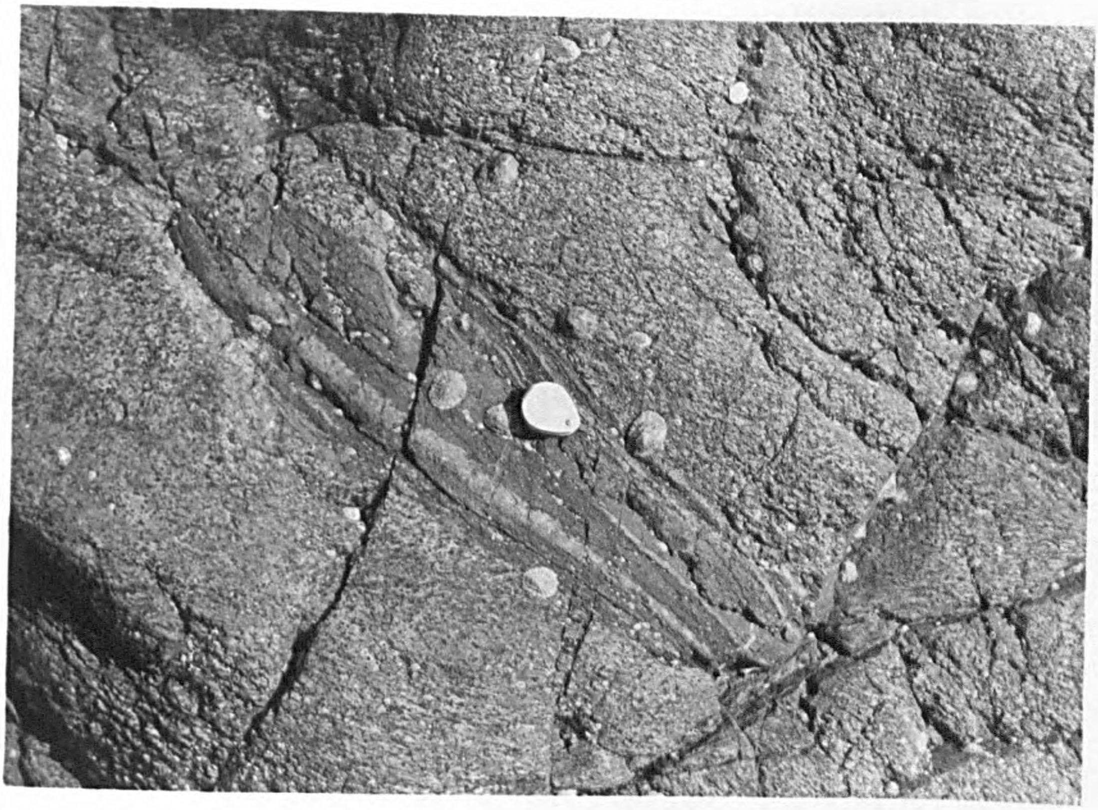
2.16 Irregular margin of late D_2 granodioritic vein, Anse de Pivette.

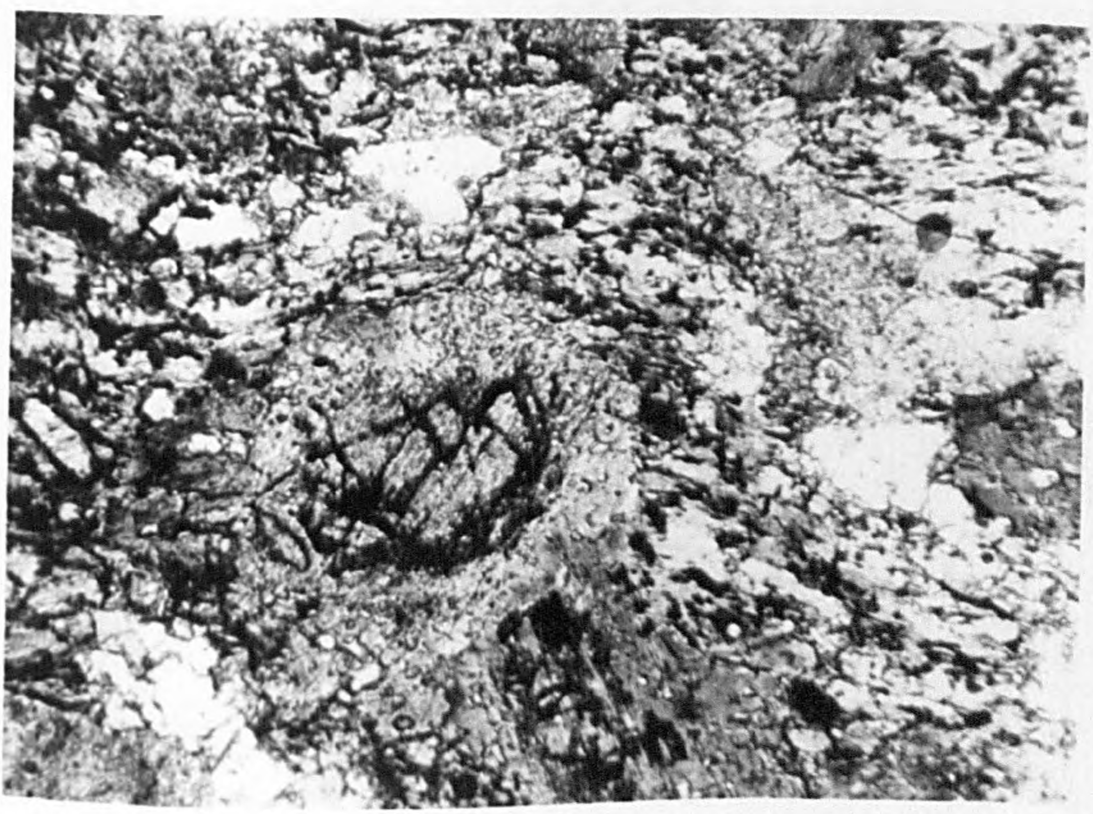




2.17 Xenolith with early banding in Nez de Voidries quartz dioritic gneiss, W side Anse de Seninval.

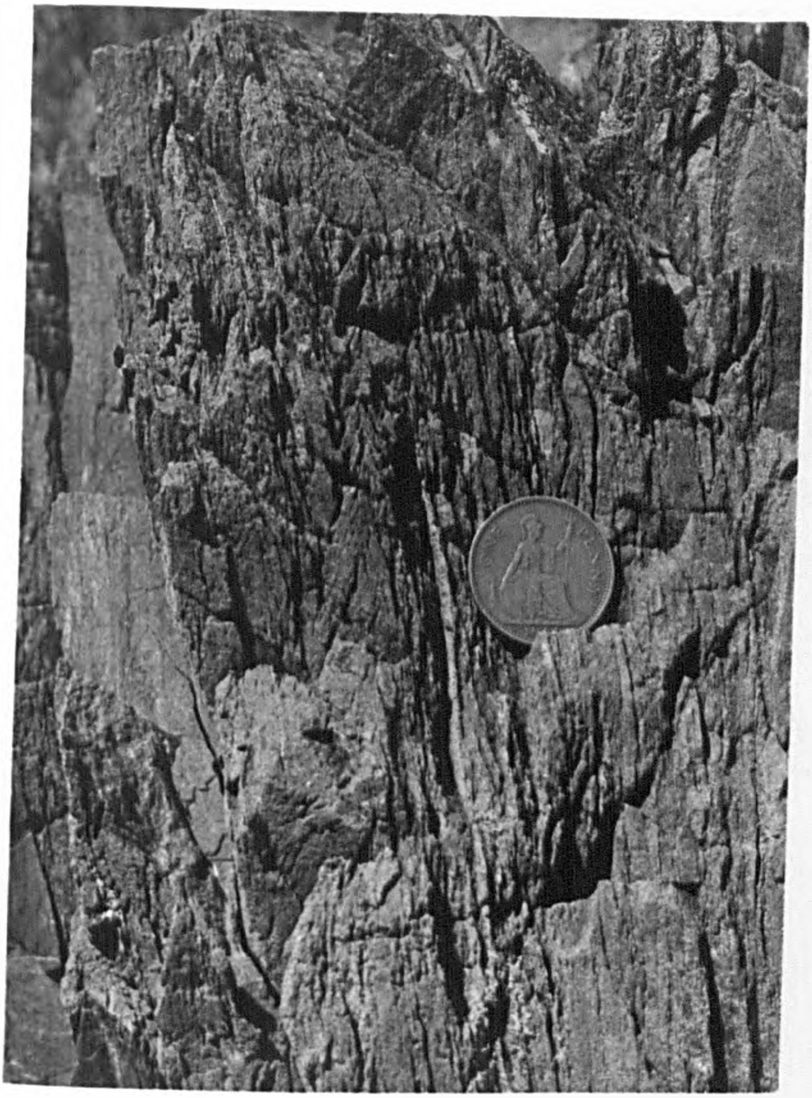
2.18 Relict core in amphibole of Nez de Voidries quartz dioritic gneiss. X32.

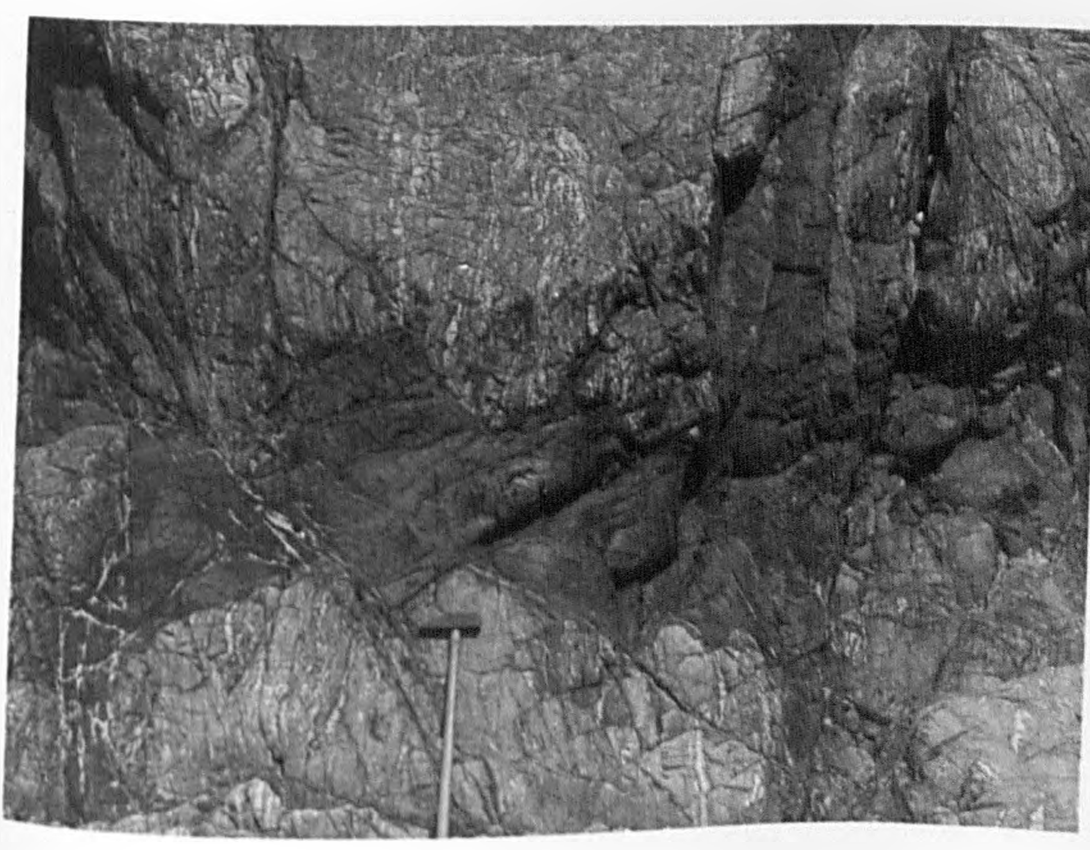




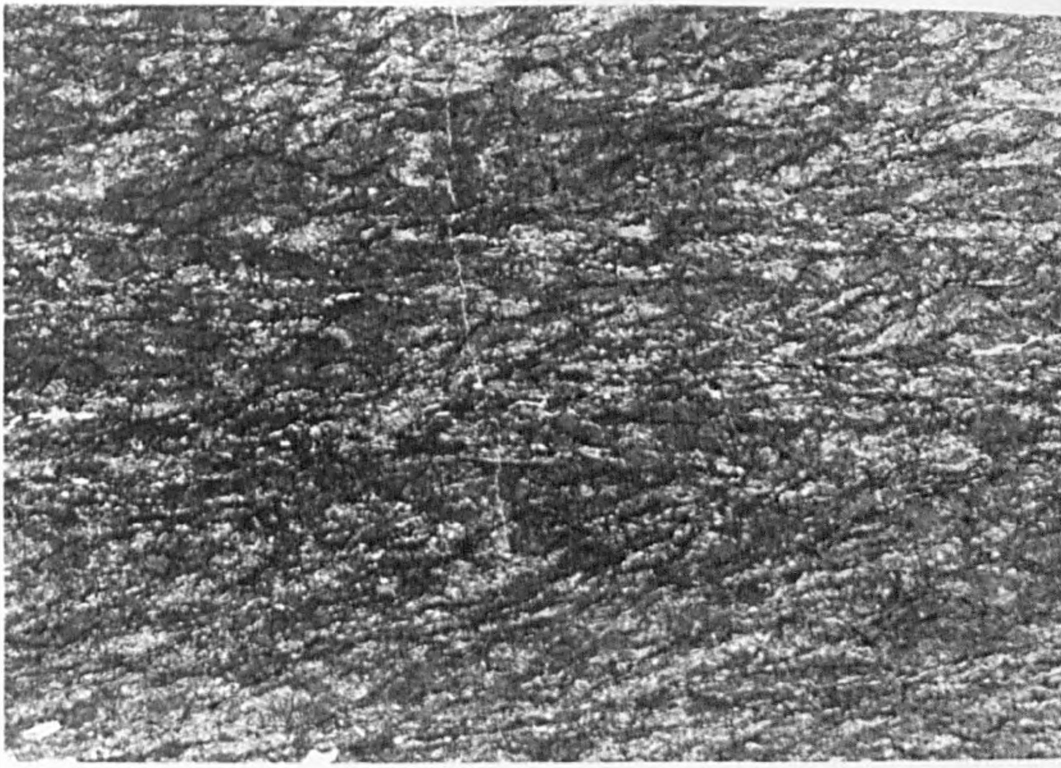
2.19 Preserved folded foliation centre left of coin, pre-D_1 basic dyke, Anse de Pivette.

2.20 Pre-D_4 basic dyke, Anse de Pivette.



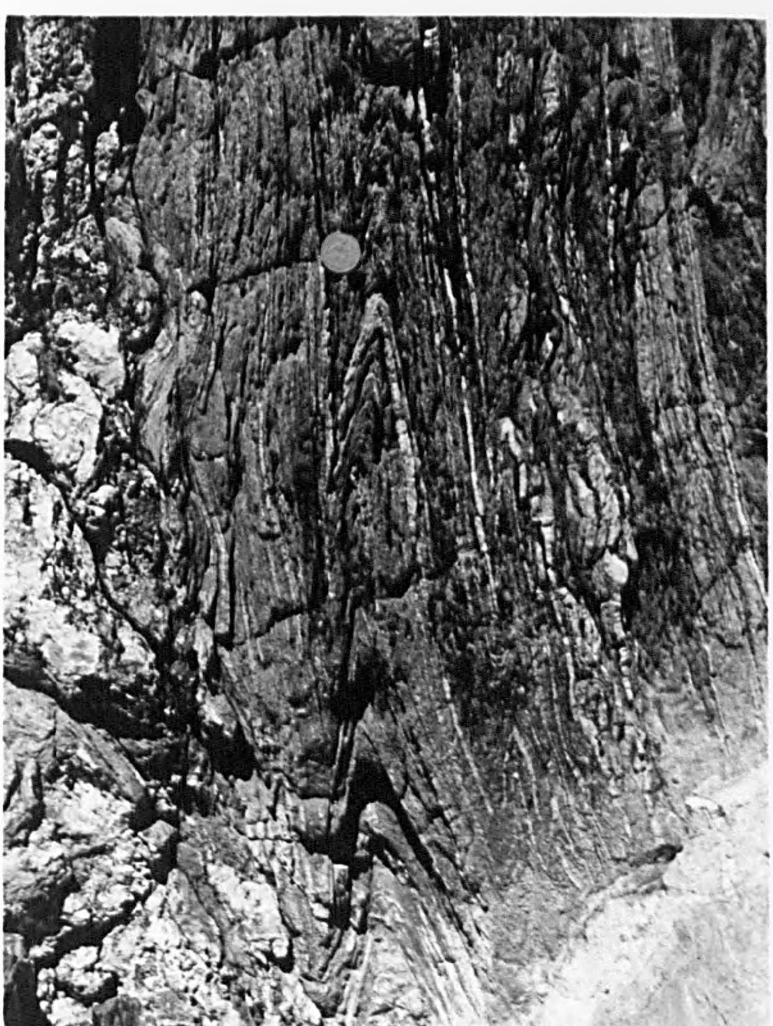


2.21 Photomicrograph of folded foliation in pre-D_1 basic dyke, Anse de Pivette. X5.



2.22 F_2 folds Anse de Pivette.

2.23 F_2 fold hinge defined by S_1 banding.
Anse de Pivette.

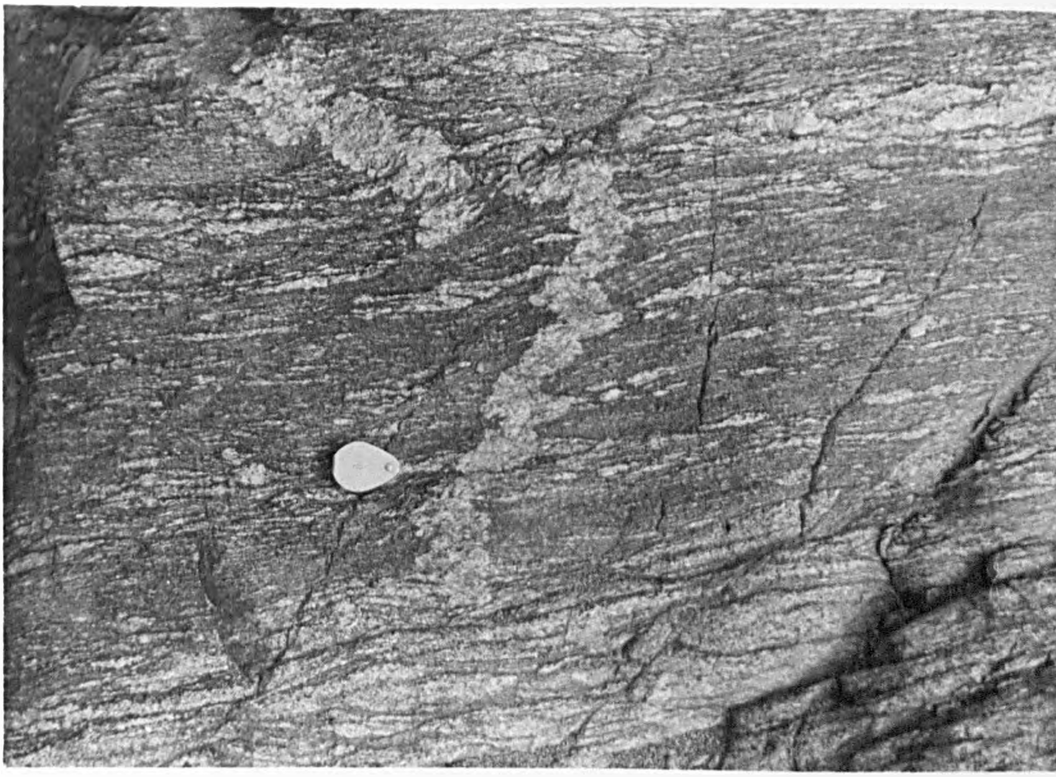


2.24 F_3 fold Anse du Culeron.

2.25 F_3 fold Anse de Seninval.

2.26 Pink acid vein cross-cuts S_2 deformed by D_3, Anse du Culeron.

2.27 D_3 folding, Anse de Seminval.



CHAPTER 3

THE THIEBOT ORTHOGNEISS COMPLEX

Exposure of the complex occurs along the south coast from Pointe du Bec de l'Ane in the west to Le Houguet in the east, a distance of nearly 4 km. The inland extent of the outcrop of the complex varies from several hundred metres at the eastern end to about 2 km at the western end, (see end maps 1 and 2).

Jérémine (1930) described the rocks of this part of the south coast as a series of granites that had injected former sedimentary rocks and finally suffered shearing in a direction close to north-east. She visualised the granites as being similar but with small differences in composition as might have arisen by differentiation of a single magma.

Field mapping shows that the Thiebot orthogneiss complex may be divided into three principal rock types, the Moulinet quartz dioritic gneiss, the Thiebot granodioritic gneiss and the Red granitic gneiss, all having a similar near N-S trending steeply dipping foliation (S_4), see table 2.1 for details.

At the eastern boundary of the complex at Le Houget the Moulinet quartz dioritic gneiss is in faulted contact with coarse grained conglomeratic Cambrian arkoses. This is the only exposed contact between the complex and Cambrian sediments, however it may be inferred from inland mapping that the complex underlies Cambrian and Ordovician sediments and is therefore probably Precambrian in age. This conclusion is supported by the isotopic age determinations (Leutwein et al., 1973) that are discussed in Chapter 8.

At the western boundary of the complex the Thiebot granodioritic gneiss is in contact with the gneisses of the Nez de Jobourg area at Pointe du Bec de l'Ane. In the cliff section to the east of this point the detailed relationships between these gneisses may be clearly observed. The contact, in places, runs nearly E-W and is at right-angles to the main foliation and banding in the gneisses of the Nez de Jobourg area. Small, anastomosing veins emerge from the Thiebot granodioritic gneiss into these gneisses cutting across the foliation and stoping off small fragments into the veins (see plates 3.1 and 3.2). There is little decrease in grain size apparent in the Thiebot gneiss approaching the contact and the foliation is almost normal to the contact and parallel to that in the gneisses of the Nez de Jobourg area. To the west side of Pointe du Bec de l'Ane the age relationships between the gneisses may be established further. Here the gneisses of the Nez de Jobourg area are represented by a foliated quartz dioritic material. Cutting across this foliation is a basic dyke several metres long and about 1 m wide. The dyke is itself truncated by the contact of the Thiebot granodioritic gneiss (see plate 3.3). Thus the Thiebot granodioritic gneiss is not only younger than the main foliation in the gneisses of the Nez de Jobourg area but also later than a phase of basic dyke intrusion subsequent to the formation of this foliation.

In the section to the west of Anse du Tas de Pois the Thiebot granodioritic gneiss is again in contact with the older gneisses. Here the boundary between the two rock-types is irregular with, in some places, the Thiebot gneiss forming dykes ranging from 1 to 10 m wide tonguing into a K-feldspar augen gneiss and, in others, screens of augen gneiss standing in predominantly Thiebot granodioritic gneiss. The foliations in both rock types are essentially vertical and parallel but the Thiebot granodioritic gneiss clearly cross-cuts the foliation in the older gneiss. To the west side of Anse des Moulinets screens of K-feldspar augen gneiss up to 50 m wide are found in the Moulinet quartz dioritic gneiss.

The Moulinet quartz dioritic gneiss occurs from the eastern boundary of the complex to just west of the Anse des Moulinets. From here it is replaced by the Thiebot granodioritic gneiss and does not appear again. Unfortunately the contact relations between these two rock types have been obscured by the presence of a further minor rock type, the Fontenelles granodioritic gneiss, which forms a dyke about 50 m wide intruded along the contact zone. It contains recognisable xenoliths up to 30 cm in diameter of the Thiebot granodioritic gneiss. The only evidence of the relative ages of the Moulinet quartz dioritic gneiss and the Thiebot granodioritic gneiss is the presence of quartz dioritic xenoliths, among them a raft 5 m by 3 m, in the Thiebot gneiss at its closest point to the Moulinet gneiss. These are all extremely weathered and it is only possible to postulate they are most likely to be of the Moulinet quartz dioritic gneiss and that the Thiebot granodioritic gneiss is probably younger than the Moulinet quartz dioritic gneiss.

The Moulinet quartz dioritic gneiss is never found in contact with the Red granitic gneiss. Rafts and xenoliths of a coarse grained granitic rock with red K-feldspar porphyroblasts were found in the Moulinet quartz dioritic gneiss on the north-west side of the Baie des Fontenelles close to a younger intrusive granitic sheet. They showed a superficial resemblance to the Red granitic gneiss. Texturally, however, they lack a mineral foliation and the K-feldspar grains are much more euhedral and equidimensional in form than those in the Red granitic gneiss. A modal analysis showed that the rafts are more granodioritic in composition than the typical Red granitic gneiss. Exactly similar rocks do not have a continuous outcrop anywhere in La Hague. It seems unlikely that they have the same origin as the Red granitic gneiss especially as they occur in close association with blocks of banded acid gneiss and of amphibolite included in the Moulinet quartz dioritic gneiss and probably derived from the Nez de Jobourg gneisses.

The Thiebot granodioritic gneiss outcrops from Pointe du Bec de l'Ane as far as the west side of the Baie de la Gravelette and again west and east of Anse du Tas de Pois. Between these two occurrences the Red granitic gneiss is found. On the east side of the Red granitic gneiss to the west of Descente de Perréval the contact between the two rock types is sharp. However, only about 2 m of the contact zone is exposed on a beach section covered with massive boulders. The contact and the foliations in both rock types are parallel and a vein 30 cm wide is emplaced along the contact rendering any deductions about relative age impossible. On the west side of the outcrop of the Red granitic gneiss the relationship with the Thiebot granodioritic gneiss is no more certain. Coming east from Pointe du Bec de l'Ane the most prominent change is the sudden decrease in the number of xenoliths present in the Thiebot granodioritic gneiss. This occurs abruptly at a zone of shearing and cataclasis 30 m wide in the gneiss to the west of the Baie de la Gravelette. From this point going east the gneiss in the Baie de la Gravelette has virtually no dark xenoliths, whilst that to the west has fairly abundant xenoliths (see plate 3.4). This change is taken as the boundary between the Thiebot granodioritic gneiss and the Red granitic gneiss. However, it is not until the east side of Baie de la Gravelette that the Red granitic gneiss begins to contain noticeably more pink K-feldspar than the Thiebot gneiss and this boundary may be partly transitional. Certainly no sharp contacts are present.

The Red granitic gneiss is cut close to its eastern margin by a comparatively minor rock type referred to as the "dark phase". This is a granodioritic gneiss rich in mafic minerals which forms a zone of dykes and veins about 60 m wide. Within the dykes, angular blocks of the foliated Red granitic gneiss are visible and the "dark phase" is clearly younger than the Red granitic gneiss.

The other comparatively minor rock type is the Fontenelles granodioritic gneiss which has already been mentioned as occurring along the contact between the Moulinet quartz dioritic gneiss and the Thiebot granodioritic gneiss. It is also found on the east side of the Baie des Fontenelles in a zone about 75 m wide within the Moulinet quartz dioritic gneiss. On the east side the contact between the two rock types is sharp. However, there is no decrease in grain size approaching the contact and no veins could be found. The foliation is parallel in both rock types and passes undeflected across the contact almost at right angles to it. On the west side the contact is much more transitional and may only be positioned approximately. The Fontenelles granodioritic gneiss is also found as veins within the Thiebot granodioritic gneiss but they are usually quite narrow ranging from 10 cm up to several metres wide and are most common at Perréval.

In summary, the field evidence allows the recognition of several different rock types in the complex but does not allow the establishment of the unambiguous relationships between them. The Moulinet quartz dioritic gneiss is probably the oldest member of the complex and is followed by the Thiebot granodioritic gneiss. The Red granitic gneiss may result from a gradual change in the Thiebot granodioritic gneiss rather than be a separate intrusive phase. The Fontenelles granodioritic gneiss is younger than the Thiebot granodioritic gneiss and the "dark phase" younger than the Red granitic gneiss. Granted the assumption that the quartz dioritic rafts in the Thiebot gneiss are of Moulinet gneiss then the Moulinet gneiss must have been solid before the intrusion of the Thiebot granodioritic gneiss. Similarly the Thiebot granodioritic gneiss must have been solid before the intrusion of the Fontenelles granodioritic gneiss and the Red granitic gneiss before the intrusion of the "dark phase".

The Moulinet Quartz Dioritic Gneiss

The Moulinet quartz dioritic gneiss is a medium grained, fairly massive rock. It is characteristically light blue-grey in colour with a foliation picked out by the mafic minerals. Very dark xenoliths are fairly common within the gneiss but are usually less than 5 cm in diameter. They are rounded but rarely elongate parallel to the foliation and do not themselves have a penetrative foliation. There is a slight tendency for mafic minerals to be more concentrated in the diorite around the margins of the inclusions.

In thin section the Moulinet quartz dioritic gneiss is an inequigranular rock with a mean grain size of about 2 mm and a colour index of between 20 and 40. Plagioclase forms a granular mosaic with quartz occurring interstitially. Aggregates of anhedral hornblende and biotite define a coarse, irregular foliation in the rock. Accessory minerals are varied and include apatite, sphene, epidote, magnetite and prehnite.

Plagioclase (about 50%) is subhedral, varying from lath-shaped grains to equidimensional tablets showing well developed albite and occasional Carlsbad twinning. It is andesine in composition (An_{30}-An_{38}) and is often extremely altered to sericite and epidote. Some grains show continuous zoning. The plagioclase crystals may be deformed with granulated margins and twin lamellae bent. Hornblende (about 15%), α : pale green, β : green and γ : dark green and extinction angle γ : c : 17°, varies in grain size from 0.2 to 2 mm. It forms ragged, anhedral grains with a patchy colouration. Some grains show simple twinning and most contain inclusions which may be quartz, apatite, magnetite and sphene. Green biotite and chlorite are often developed around the margins of the hornblende and appear to be replacing it.

Biotite (about 10%), α : golden yellow, β , γ : dark brown or green, is commonly in flakes about 1 mm long associated with hornblende. It shows alteration along the cleavage to chlorite and contains inclusions of magnetite and apatite. Sometimes prehnite is abundantly developed along the cleavage planes. Cleavage traces may be kinked showing signs of deformation.

Quartz (16%) occurs as aggregates of up to 2 mm in size and as small grains filling interstitial areas between the plagioclase crystals. Undulose extinction is common.

K-feldspar may vary from 0 to 5% and is usually about 2%. It is a late replacive mineral forming rims on plagioclase crystals but mainly occurring interstitially. It shows fine scale perthitic patches and veins and cross-hatch twinning.

Apatite occurs as euhedral prisms up to 0.3 mm long often included in biotite and hornblende. Sphene is present in accessory amounts sometimes as isolated euhedral grains. Prehnite may be found in quantities up to 1% in some samples. It is developed along the cleavage in biotite flakes forming barrel shaped aggregates up to 1 mm long.

The Thiebot Granodioritic Gneiss

The Thiebot granodioritic gneiss is a light coloured rock usually medium grained, but showing variations in grain-size and also in the intensity of the development of the foliation. Within the main outcrop of the gneiss a characteristic feature is the occurrence of darker inclusions. These vary in size up to about 10 cm and are usually elongate in the plane of the foliation. The foliation in the gneiss appears to pass through the inclusions and is not displaced around them.

The dominant minerals of the gneiss are plagioclase quartz and K-feldspar. Some hornblende is usually present together with variable amounts of biotite and chlorite. The colour index ranges between 10 and 20 with an average value of about 12. The texture is variable but often shows slightly augen-shaped plagioclase grains 2-4 mm in size surrounded by bands of quartz. K-feldspar is usually closely associated with the plagioclase forming rims around the grains and sometimes partly replacing them.

Plagioclase (40-53%) varies in grain size from 1-4 mm. It is subhedral and fairly equidimensional in shape but with a tendency to show curved margins parallel to the foliation. It may occur in more plagioclase rich bands of several grains in width. The composition is sodic oligoclase (An_{12}-An_{15}) and some Carlsbad and thin albite twinning is developed. Both continuous and oscillatory zoning are fairly common. The plagioclase is often extensively altered to sericite and some deformation twinning may be seen.

Quartz (18-35%) is often intensely recrystallised in bands up to 6 mm wide which taper out along their length and are composed of smaller (0.2-2 mm) grains showing dimensional orientation. Grain boundaries range from straight to serrate with straight boundaries often parallel to the foliation.

K-feldspar (11-16%) shows a range of grain size from 1 to 4 mm.

Perthitic textures are sporadically developed with thread, rod and patch perthites being the more usual forms, although braid perthite is occasionally found in the larger grains of some specimens. Cross-hatch twinning is not often visible although it does occur in some strained crystals showing undulose extinction. Carlsbad twinning is rare. The K-feldspar is often interstitial and closely associated with the plagioclase, sometimes replacing it. Polygonal recrystallisation of the K-feldspar is seen along cracks in the grains and sometimes at the grain boundaries. Some grains are completely replaced by a mosaic of polygonal grains. Myrmekitic growths are developed at some K-feldspar grain boundaries but they are not abundant.

Hornblende (1-6%) forms ragged, poikilitic crystals 1-2 mm in size, characteristically associated with biotite, magnetite and chlorite. The pleochroic scheme is α : straw yellow, β : brown green and γ : dark green, $\gamma : c = 17^{\circ}$. Simple twinning is sometimes present.

Biotite (3-12%) may occur as single flakes 1-3 mm in size or in aggregates of flakes of less than 0.5 mm in size. Pleochroic schemes α : golden yellow, β : brown, γ : dark brown-black and α : straw yellow, β , γ : green are both found. The flakes may be full of fine inclusions of magnetite, quartz and epidote.

Chlorite usually occurs in only minor amounts, although locally it may exceed 5% and is usually in small (1 mm) ragged flakes associated with and sometimes replacing the other mafic minerals. Apatite and epidote occur in accessory amounts and rare, isolated, zoned grains of orthite may also be found.

In thin-section the dark xenoliths show a mineral assemblage of plagioclase, hornblende, biotite and quartz with a grain size in the range 0.1-0.3 mm, that is much finer than the granodioritic gneiss.

The margins of the xenoliths are usually irregular and slightly gradational in detail. The plagioclase is sodic oligoclase (An_{11}) and it is anhedral with some albite twinning and zoning. Rare grains may be up to 1 mm in size. Hornblende occurs as euhedral prisms with a slightly broken appearance. The pleochroic scheme is α : yellow, β : green and γ : green and some simple twinning is developed. Biotite, α : golden yellow, β , γ : dark brown, forms flakes along grain boundaries which are either compact or very ragged in outline. It also occurs as aggregates of interlocking laths. Quartz is seen as euhedral straight sided grains.

The Red Granitic Gneiss

The Red granitic gneiss is an inequigranular, medium to coarse grained rock. It is resistant to erosion and forms massive buttresses and cliffs which descend almost directly into the sea. It has a fairly well developed foliation throughout, although the intensity of its development is variable. Biotite is in slightly curved, drawn out aggregates and the leucocratic minerals also tend to be drawn out into discontinuous lenses and stringers forming the foliation.

In thin-section the Red granitic gneiss shows a range of grain size of about 2-4 mm and a colour index of about 6. The principal minerals present are quartz, plagioclase and K-feldspar but their relative proportions vary quite considerably. Biotite and chlorite are the only mafic minerals. Hornblende is absent.

Plagioclase (25-44%) is albitic in composition (An_8) and usually extensively altered. It commonly varies in grain-size from 2-4 mm and is usually anhedral. In the more deformed rocks the plagioclase appears augen-like in shape. Continuous zoning is a common feature of most grains but oscillatory zoning does also occur. Some fine albite twin lamellae are developed but many grains appear untwinned.

K-feldspar (25-38%) varies in size from 0.2-4 mm and tends to be anhedral. The grains are never strongly perthitic although thread and patch perthites do occur. Carlsbad twinning is not common and cross-hatch twinning occurs only infrequently and is poorly developed. Small (0.3 mm) plagioclase crystals may be enclosed by the larger grains and smaller patches of K-feldspar may be developed on the margins of plagioclase grains. A common feature of many of the larger grains is the development of a myrmekitic wart-like growth on the grain boundaries growing convex into the K-feldspar. These growths may reach 0.3 mm in width and are seen at plagioclase-K-feldspar boundaries, but also occur at boundaries between K-feldspar and quartz and between pairs of K-feldspar grains. The more deformed crystals show undulose extinction and fractures across the grains and are elongated in the direction of the foliation. Small patches of K-feldspar may be found interspersed in the quartz-rich areas.

In the larger grains along fractures parallel or oblique to the foliation, areas of polygonal grains of K-feldspar 0.2 mm in diameter are developed. In the more deformed examples complete replacement of the larger crystals by polygonal grains has taken place. Besides development along fractures there is also a tendency for polygonal grains to occur along grain margins, again in the more deformed examples.

Quartz (22-43%) occurs predominantly in stringers of varying width and length between the other minerals. The state of deformation and size of the grains also varies. In some thin-sections grains up to 2 mm wide with undulose extinction and fractures parallel to the foliation may be seen. In others, the quartz is finer grained and elongated parallel to the foliation by a length to breadth ratio of up to 8:1 and forms bands swirling around the other minerals. Quartz-

quartz grain boundaries vary from straight to lobate and serrate.

Biotite (1-5%), α : pale yellow, β , γ : green or brown, is the principal mafic mineral but variable amounts of chlorite occur in some specimens. Single, isolated flakes may reach 1-2 mm in size but flakes forming aggregates are usually less than 0.5 mm in size. The aggregates are associated with quartz, apatite and magnetite. Biotite may sometimes show alteration to chlorite along the cleavages.

The "dark phase" cutting the Red granitic gneiss is a medium grained well foliated rock characterised by about 20% of biotite as the dominant mafic mineral. Subhedral plagioclase and subordinate K-feldspar are surrounded by bands of quartz with a tendency for the biotite to be more concentrated parallel to the margins of the quartz bands.

Plagioclase (about 38%) is subhedral to rounded and 2-3 mm in size. It is sodic oligoclase in composition (An_{10}) and shows well developed albite twinning and complex oscillatory zoning.

Quartz (about 30%) occurs in elongate areas up to 5 mm long composed of grains less than 1 mm in size. The grain boundaries are straight to complex and serrated and show marked dimensional orientation. The larger grains have undulose extinction.

K-feldspar (about 13%) is anhedral and ranges in grain-size up to 3 mm. There are few signs of perthitic texture and no cross-hatch twinning. The grains are sometimes rimmed by myrmekitic growths but these are not abundantly developed. Larger grains show polygonal recrystallisation along margins parallel to the foliation and interstitial K-feldspar may be completely polygonal.

Rare grains of poikilitic green hornblende, α : straw yellow, β : pale green, γ : green, up to 1 mm in size do occur associated with biotite.

Biotite (about 18%), α : pale yellow, β : brown, γ : dark brown, is the main mafic mineral. Flakes up to 1 mm in size grow alongside quartz rich bands and along grain boundaries in plagioclase. Larger flakes, up to 3 mm long, also occur often associated with the smaller flakes. Inclusions of apatite, magnetite, quartz and sphene are found in the biotite.

Accessory allanite forms isolated elongate grains 1 mm long showing a patchy brown colouration, zoning and simple twinning.

The Fontenelles Granodioritic Gneiss

The Fontenelles granodioritic gneiss is a medium grained rock weathering to a reddish-brown colour. On freshly broken surfaces it appears quite colourful with greenish plagioclase and red K-feldspar standing out from a blue-grey background. Occasional porphyritic K-feldspar crystals may be found up to 1 cm long. Some small mafic xenoliths occur within the gneiss and also larger rounded xenoliths up to 20 cm in diameter of a red porphyritic granite.

In thin-section the Fontenelles gneiss is seen to be composed of dominant plagioclase and subordinate quartz and K-feldspar. The colour index is less than 20 and the usual mafic minerals are ragged, altered hornblende and biotite together with more abundant chlorite.

Plagioclase (about 50%) is 2-4 mm in grain-size and subhedral to anhedral. It is sodic oligoclase in composition (An_{12}) and shows Carlsbad and albite twinning and some slight zoning. The plagioclase is often intensely altered to sericite and epidote and sometimes has granules of sphene growing in it.

K-feldspar (about 15%) is up to 4 mm in size but more often about 2 mm in size and occurs interstitially or forming partial rims around plagioclase. It is usually anhedral and only slightly perthitic. Cross-hatch twinning is developed and some Carlsbad twins may be seen with irregular composition planes. Quartz forms small interstitial areas composed of grains with almost straight boundaries and euhedral form. Larger (up to 3 mm) grains often show fractures and undulose extinction.

Hornblende (less than 5%), α : straw yellow, β : brown-green, γ : dark green and extinction angle, γ: c = 15°, occurs as euhedral to ragged grains up to 1 mm in cross-section and 2 mm long sometimes showing simple twinning. It is nearly always associated with chlorite and contains inclusions of magnetite and commonly shows a patchy colouration.

Chlorite (about 10%) occurs as 1 mm flakes replacing hornblende and containing inclusions of magnetite, prehnite and epidote. Some biotite, α: pale yellow, β : pale green, γ : green, may be associated with the chlorite.

Accessory sphene, apatite and rare zoned allanite also occur.

<u>Summary of Petrography of the Thiebot Complex</u>

The petrography of the rocks of the Thiebot orthogneiss complex appears to be dominantly controlled by three factors: variation in the relative proportion of minerals present, the intensity of the deformation and the degree of alteration.

In passing from the Moulinet quartz dioritic gneiss via the Thiebot granodioritic gneiss to the Red granitic gneiss a number of differences may be observed (see tables 3.1 and 3.2). The proportion of plagioclase decreases and it becomes increasingly albitic in composition. Hornblende and biotite decrease in amount with no hornblende being found in the Red granitic gneiss. K-feldspar increases in amount and so does quartz although quartz shows a wide variation in the proportion present. Some of these features may be seen in figure 3.1 where the proportions of plagioclase, quartz and K-feldspar

	Moulinet Quartz Dioritic Gneiss	Thiebot Granodioritic Gneiss	Red Granitic Gneiss	Fontenelles Granodioritic Gneiss	Dark Phase
Plagio-clase	Around 50% An_{30}-An_{38}	40-53% An_{12}-An_{15}	25-44% An_{8}	About 50% An_{12}	38% An_{10}
K-feldspar	0-5% Late; replacive; rims around plagio-clase. Some fine scale perthite; some cross-hatch twins	11-20% Interstitial and rims around plagioclase. Sporadic perthite; Rare cross-hatch twins; polygonal recrysta-llization; Some myrmekite.	20-38% More abundant grains; Some perthite; Rare cross-hatch twins; polygonal recrysta-llization. Myrmekitic rims more common.	About 15% Interstitial and rims; Slightly perthite; Some cross-hatch twins.	13% Little perthite; No cross-hatch twins; polygonal recrystalliza-tion.
Quartz	16% interstitial; some aggregates.	18-35% bands; dimensional orientation.	22-43% stringers dimensional orientation.	20%	30%
Horn-blende	Around 15%; altered; ragged; inclusions.	1-6% ragged poikilitic crystals	No hornblende	Rare	Very rare
Biotite	About 10%	3-12%	1-5%	Rare	18%
Chlorite	Up to 5%	Up to 5%	Up to 5%	About 10%	-

TABLE 3.1

SUMMARY OF SOME OF THE MORE TYPICAL FEATURES OF THE PETROGRAPHY OF THE ROCKS OF THE THIEBOT COMPLEX

Moulinet Quartz Dioritic Gneiss

	24	325	4	128	21
Quartz	16.5	16.3	17.0	13.8	17.4
Plagioclase	41.7	49.9	59.7	53.1	53.2
K-feldspar	0.0	5.6	3.3	1.1	0.6
Hornblende	24.1	15.7	8.6	18.7	12.7
Biotite	11.0	11.6	3.4	8.3	14.0
Chlorite	3.4	0.2	5.6	2.8	1.0
Ore	1.1	0.4	0.3	0.4	0.5
Q	28.4	22.7	21.3	20.3	24.4
P	71.6	69.5	74.6	78.1	74.7
A	0	7.8	4.1	1.6	0.9
F	100	89.9	94.8	98.0	98.8
M	41.8	31.0	19.7	30.5	28.5
Counts	1564	2060	2051	2702	2648

TABLE 3.2

MODAL ANALYSES OF ROCKS FROM

Thiebot Granodioritic Gneiss

126	120	344	352	660	332
22.2	35.0	18.4	31.5	24.1	24.8
53.3	40.1	45.6	39.1	48.6	43.7
11.4	13.6	16.4	20.0	15.7	16.4
3.2	3.3	5.8	-	1.2	2.8
4.5	6.4	12.4	0.6	0.1	9.6
4.0	0.2	1.1	8.3	7.7	0.9
0.8	1.1	0.3	0.6	2.7	1.7
25.5	39.5	22.9	34.8	27.3	29.2
61.3	45.2	56.7	43.2	55.0	51.5
13.1	15.3	20.4	22.1	17.8	19.3
82.4	74.7	73.5	66.2	75.5	72.7
13.1	11.4	19.6	9.5	11.7	15
1524	1286	2730	2349	2168	2456

THE THIEBOT COMPLEX

	Red Granitic Gneiss									Dark Phase	Fontenelles
	342	341	726	340	466	467	470	356	515	516	9
Quartz	23.0	39.3	36.7	25.8	25.8	22.1	27.6	37.8	43.2	30.4	23.7
Plagioclase	49.7	35.7	42.3	32.3	39.1	43.5	31.6	28.0	25.1	37.9	47.0
K-feldspar	21.8	20.9	18.5	37.6	27.6	29.8	34.8	28.7	25.3	13.4	14.3
Hornblende	-	-	-	-	-	-	-	-	-	-	3.5
Biotite	3.1	2.0	2.4	3.8	0.6	1.1	5.3	5.0	5.1	18.0	1.8
Chlorite	1.6	2.0	-	0.2	6.1	3.0	0.2	-	-	-	7.7
Ore	0.8	0.1	0.2	0.1	0.9	0.5	0.4	0.5	1.4	0.2	1.0
Q	24.3	41.0	37.6	27.0	27.9	23.2	29.4	40.0	46.2	37.2	27.9
P	52.6	37.2	43.4	39.2	42.3	45.6	33.6	29.6	26.8	46.4	55.3
A	23.1	21.8	19.0	33.8	29.8	31.2	37.0	30.4	27.0	16.4	16.8
F	69.5	63.0	69.5	53.7	58.7	59.4	47.6	49.3	49.8	73.9	76.7
M	5.5	4.0	2.6	4.4	7.6	4.6	5.9	5.5	6.5	18.2	16.9
Counts	3932	1511	2925	2429	1611	1556	3899	2438	1397	1405	1439

T A B L E 3.2 (Continued)

MODAL ANALYSES OF ROCKS FROM THE THIBBOT COMPLEX

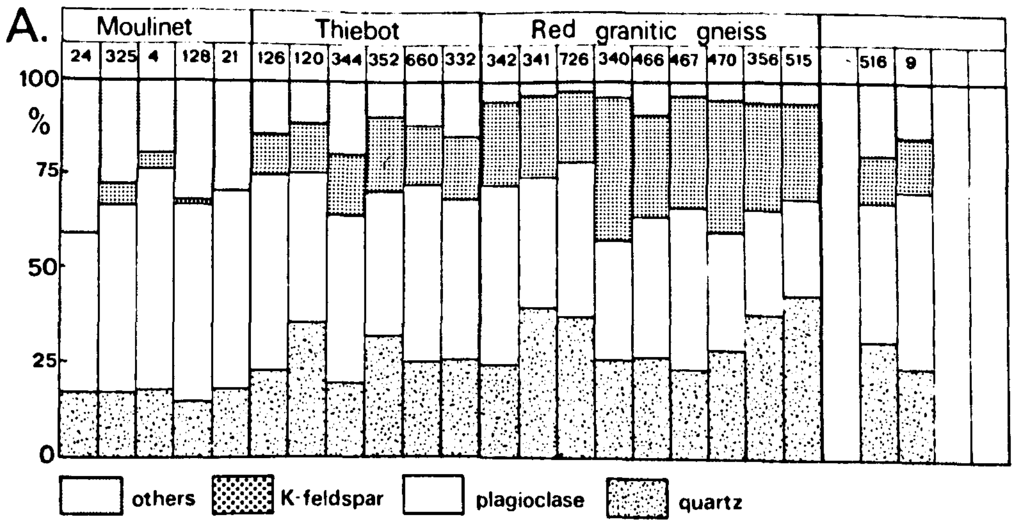
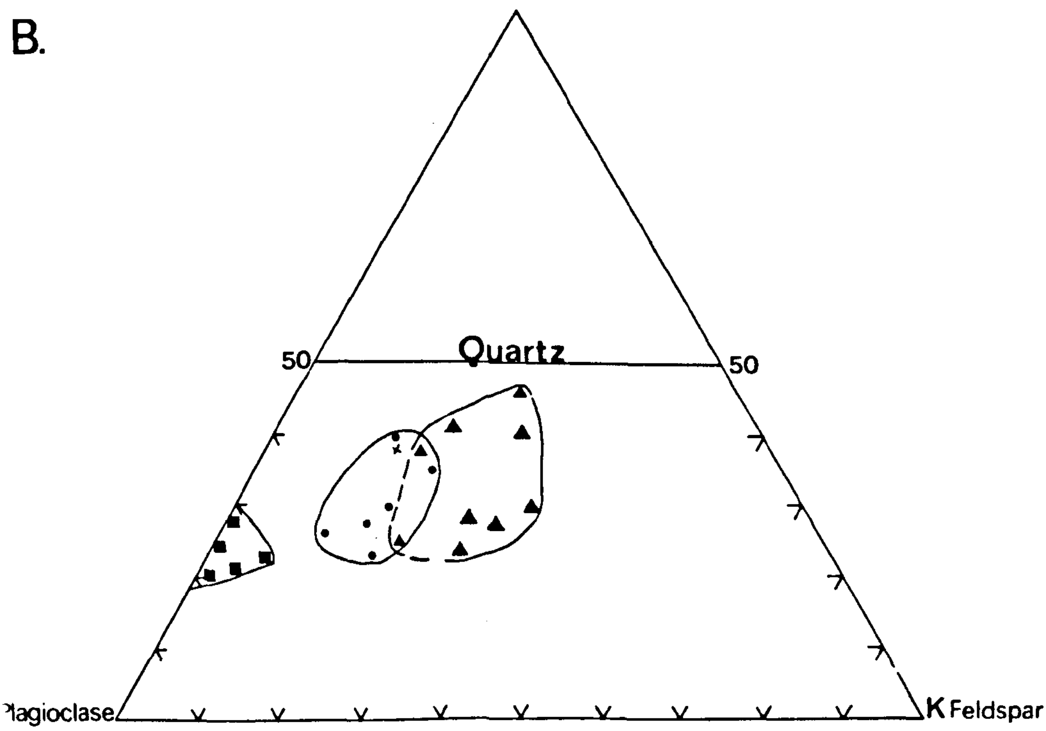


Fig.3.1 Thiebot complex, A.modal proportions. B.modal quartz, plagioclase K-feldspar recalculated to 100%.



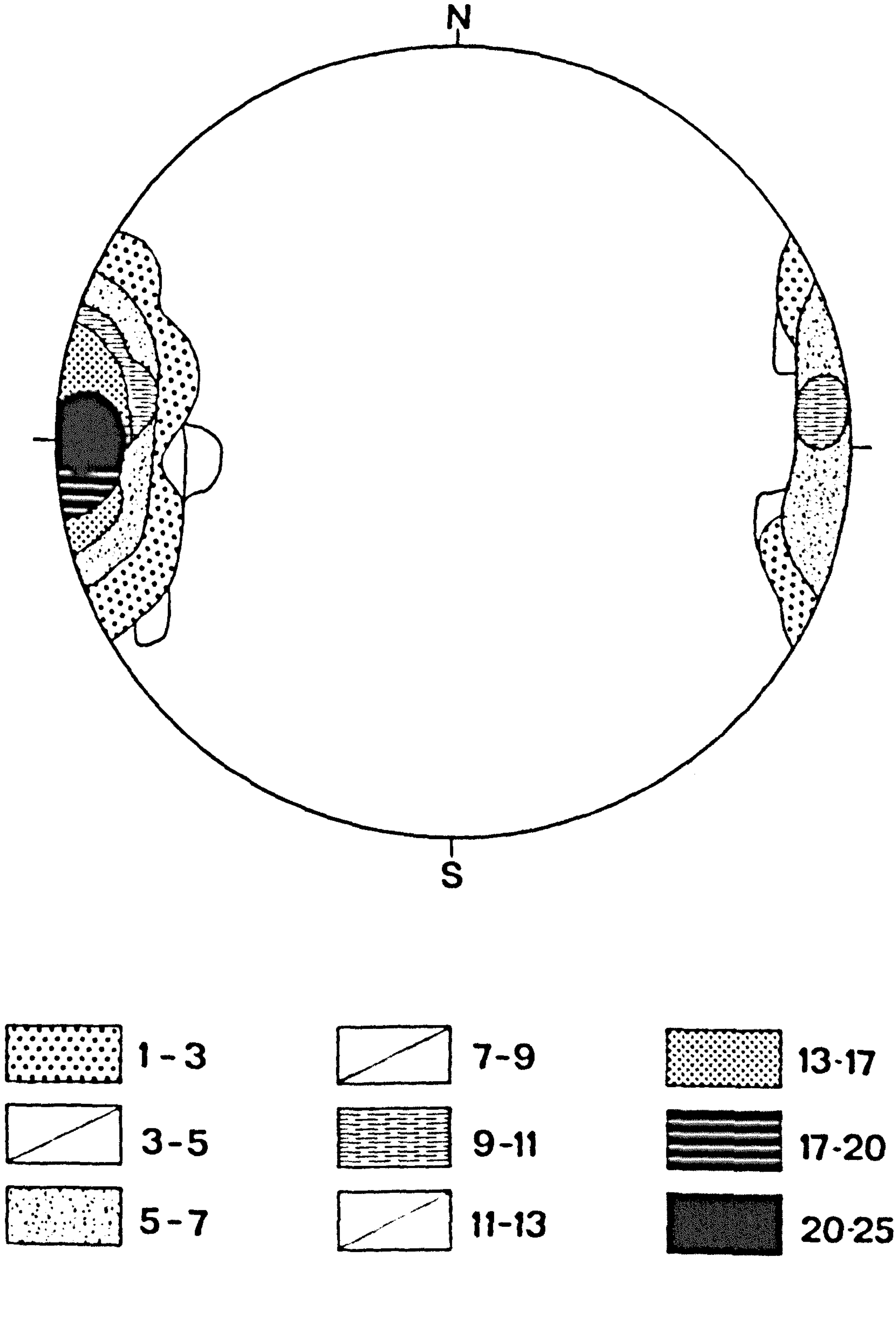
KEY: ▲ Red granitic gneiss.
• Thiebot granodioritic gneiss.
■ Moulinet quartz diorititic gneiss.
× 'Dark phase'.

for each rock modally analysed have been recalculated to 100% and plotted on a triangular diagram. The specimens from the Moulinet gneiss may be clearly distinguished as they form a separate field. Those from the Thiebot and Red gneisses are not so clearly defined although those from the Thiebot gneiss do tend to plot more towards the plagioclase apex of the triangle. The specimens from the Red gneiss which plot closest to those of the Thiebot gneiss are those which originated closest to the margin of the Red gneiss (342, 341, 726) and this supports the case for a transitional change between the two gneisses.

There is no doubt that the complex has a largely metamorphic texture and foliation. The foliation is often normal to exposed contacts and transgresses compositional boundaries. It also appears to cut through flattened xenoliths. The alignment of mafic minerals and stringers of quartz and feldspars form the foliation. Certain deformational features show a variation in the intensity of their development in different parts of the complex. Quartz may be recrystallized and show dimensional orientation. Plagioclase may have granulated grain margins and bent twin lamellae. K-feldspar may show marginal or complete polygonal recrystallization and myrmekitic rims may be developed. Biotite cleavages may be kinked. The variation in the intensity of the development of these features is not sufficiently well defined to form mappable zones although west of the Anse des Moulinets does appear to be one area where the deformation was more intense. Some of these features could have been accentuated after the formation of the main foliation.

The degree of alteration of the minerals varies throughout the complex. Thus hornblende may be seen to be altered to biotite, and biotite altered along the cleavages to chlorite. Plagioclase is often partly replaced by sericite and sometimes epidote. Prehnite is

Fig.3.2. Thiebot complex
200 poles to S_4 foliation



developed along the cleavage in biotite in the Moulinet gneiss, particularly on the west side of Anse des Moulinets. Some of this alteration, for example biotite replacing hornblende, probably dates from the original formation of the rock but some is the result of later processes, possibly retrograde metamorphism during uplift and cooling of the area.

<u>Variation in Structural State of the K-Feldspars of the Thiebot Complex</u>

The cell parameters of the phases present in a number of K-feldspar mineral separates from rock samples of the Thiebot granodioritic gneiss and the Red granitic gneiss were determined by X-ray powder diffraction techniques. The methods employed are described in the Appendix. The results are presented in tables 3.3 and 3.4 and the exact location from which the samples were collected is shown in the sketch map of figure 3.3.

Within the Red granitic gneiss, with the exception of samples 342 and 340, the dominant or only phase present is usually triclinic. Within the Thiebot granodioritic gneiss both a monoclinic and a triclinic phase are probably always present in the samples examined. However, these phases were not always sufficiently resolved by the X-ray technique employed for their separate determination.

On a b-c diagram (Wright and Stewart, 1968) the K-feldspars show a range of structural states (see figure 3.4). From their position on this diagram the triclinic feldspars from both rock types may be described as intermediate microclines. This is supported by their position on the $\alpha^* - \gamma^*$ plot (figure 3.4) and their obliquity (tables 3.3 and 3.4).

There are two important exceptions to the general variation in structural state outlined above. Samples 340 from the Red granitic

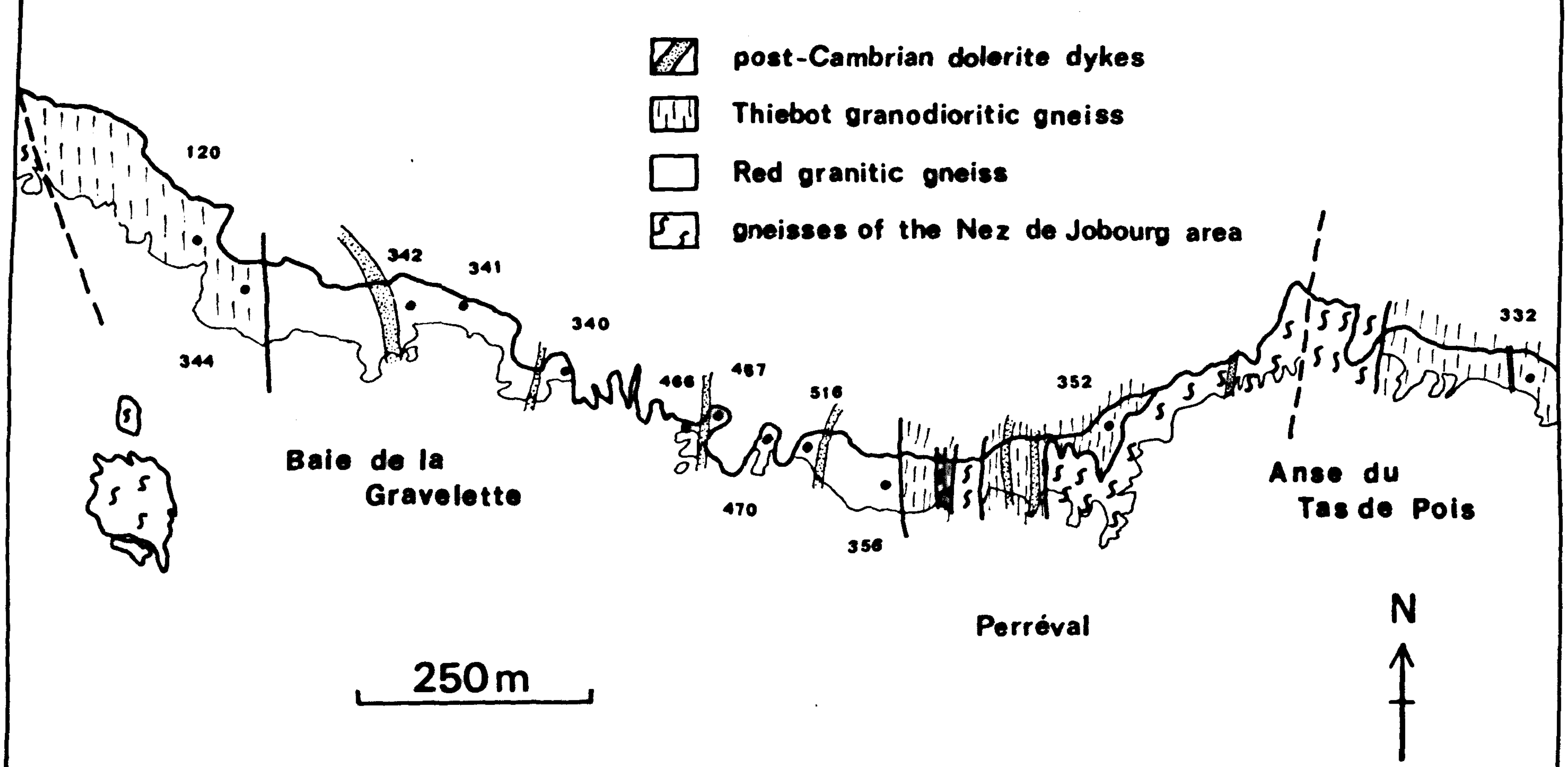


Fig. 3.3 Thiebot complex, k-feldspar sample localities.

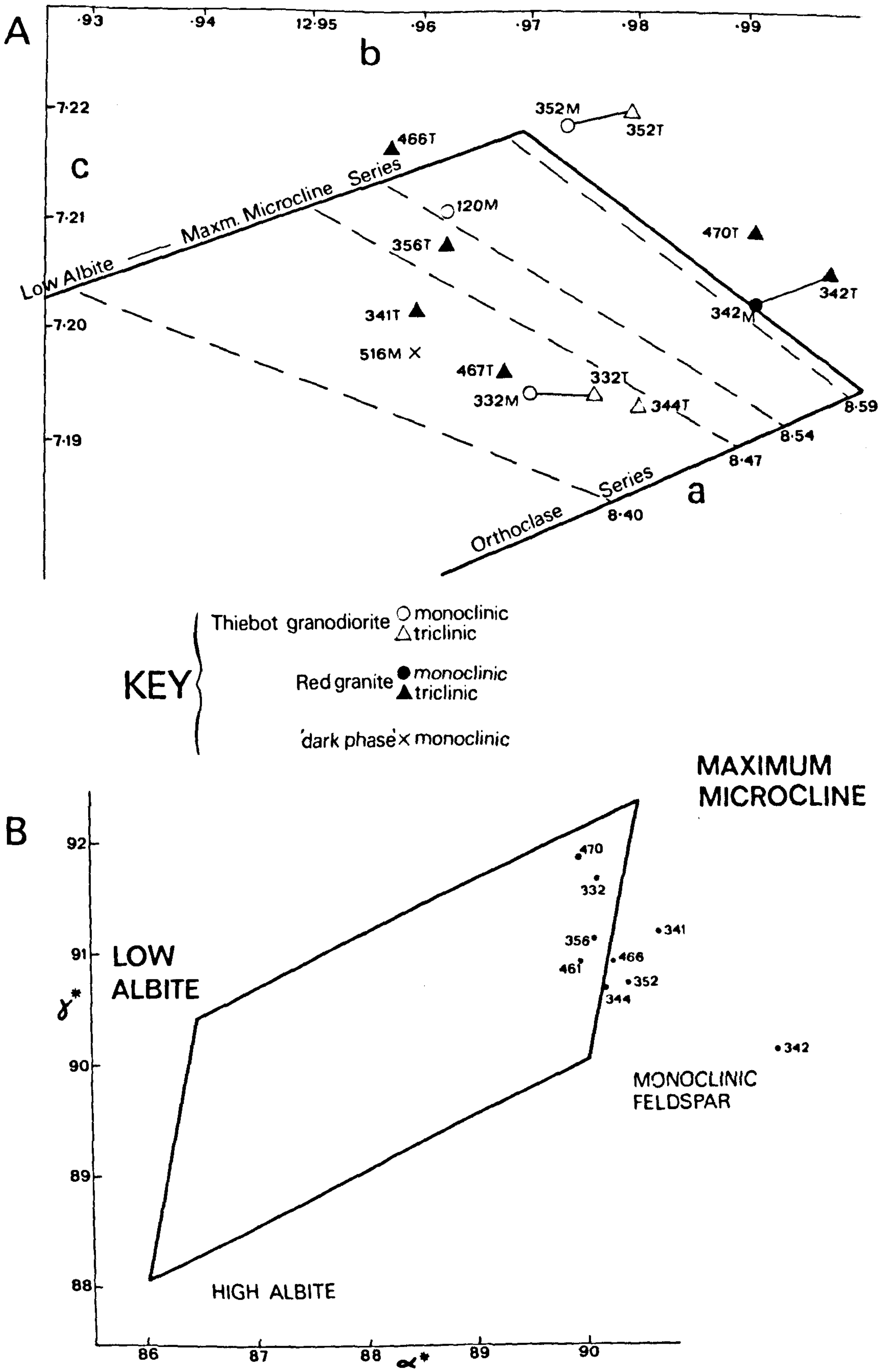


Fig. 3.4 K Feldspars from the Thiebot complex

A. b–c diagram

B. $\alpha^* - \gamma^*$ plot

gneiss and 516 from the "dark phase" both only contain monoclinic K-feldspar without any trace of the triclinic phase.

Other features of the K-feldspars of the Thiebot complex should also be mentioned. Many have anomalous "a" values (Wright and Stewart, 1968), larger than would be predicted from their position on the b-c diagram. The composition of the potassic phases, deduced from their cell volume varies between 82 and 100% Or. Those from the Red granitic gneiss tend to be more potassic than those from the Thiebot granodioritic gneiss. Where a monoclinic and a triclinic phase are found in the same rock sample, from cell volume and plotted position on the b-c diagram, the triclinic phase appears to have the higher $KAlSi_3O_8$ content.

Discussion

Temperature of crystallization, cooling rate, rate of transformation, reheating, presence of volatiles, shearing stress and variations in bulk composition are some of the factors that have been proposed as being likely to influence the eventual structural state of K-feldspars in igneous or metamorphic rocks. The particular influence which appears to be dominant may vary considerably depending on the circumstances. Any discussion of a possible interpretation of the present distribution of the structural states of the K-feldspars in the Thiebot complex may only be made bearing in mind the uncertainties as to the exact response of the polymorphs to these influences.

Following Tilling (1968) the observed variations in the structural state of the polymorphs could possibly be the result of:

1. solely primary variations resulting from temperature of formation, rate of cooling, distance from the contacts, bulk chemical composition etc.

2. completely secondary variations resulting from reheating, deformation and recrystallisation or metasomatism

3. the partial superimposition of secondary variations on primary variations such that, in part, both primary and secondary variations co-exist.

If the present distribution of structural states is the result solely of primary variation during cooling then a model for the possible sequence of events may be proposed. This would be close to that proposed by Tilling (1968) for the Rader Creek pluton, Montana where he partly explained the phase relationships present among the K-feldspars by a first order incomplete orthoclase → microcline inversion during cooling. Similarly Ragland (1970) proposed a first order transformation during cooling to explain the distribution of K-feldspar polymorphs in the Enchanted Rock batholith, Texas. He also suggested that conditions of equilibrium varied with lithology and spatial position in the batholith and that the rate of inversion was catalyzed by the presence of water. Thus perthites from the pegmatites exsolved and inverted under near equilibrium conditions to yield maximum microcline whilst those from the intermediate central zone inverted metastably and gave rise to feldspars with a range of obliquities. In the model for primary variation in the Thiebot complex the formation of orthoclase took place at a higher temperature and on cooling inverted to intermediate microcline either in part or completely depending on conditions in different parts of the complex.

Parsons and Boyd (1971) on the basis of their own investigations and many examples from the literature, emphasize the tendency for the identity of the K-feldspar in many igneous rocks to be strongly dependent on the relative bulk composition of the rock and on the rock's position in a scheme of fractionation appropriate to a particular igneous intrusion. Microcline becomes more abundant relative to orthoclase with increasing fractionation irrespective of the compositional range of the rock suites, the bulk composition of the alkali feldspars, grain size or field relations. In the model for primary variation of the Thiebot complex the influence of the bulk composition of the rock may be important. Thus the Red granitic gneiss now usually contains only microcline because it is the relatively more fractionated member of the rock suite.

If all the variation in structural state of the K-feldspars now observed in the Thiebot complex is the result of secondary processes then a model based on these processes may be proposed. In this model orthoclase would have been formed, totally replacing any earlier polymorphs as a result of reheating of the complex in a similar fashion to the orthoclase described by Steiger and Hart (1967) from a metamorphic aureole of the Eldora stock, Colorado. Intermediate microcline could have formed subsequently at the expense of the orthoclase, possibly partly as a result of stress, for example as recorded in the Foyers granite by Parsons and Boyd (1971), or more probably mostly as a result of a sluggish transformation during prolonged annealing near a suitable temperature for the orthoclase - microcline transformation, with the transformation being more complete in the Red granitic gneiss. Steiger and Hart (1967) explain the presence of a sizeable proportion of the K-feldspar in the form of intermediate microcline in one particular traverse, the Hessie traverse, away from the contact of the Eldora stock as the result of retrograde inversion of orthoclase during extended cooling resulting from the particular conformation of the contact at this point.

In either the primary or the secondary variation models the presence of orthoclase only in samples 340 and 516 may be explained by the metastable preservation of orthoclase in these rocks without inversion to microcline. Instances of this type of preservation have been commented on by other authors, particularly Marmo (1967) and Parsons and Boyd (1971) who quote examples such as xenoliths containing orthoclase in a microcline syenite. Parsons and Boyd suggest that conditions at the time of initial formation of the feldspars may be important in determining their subsequent behaviour. The trace element content of sample 516 from the "dark phase" has been shown to be distinctive and this may have influenced the final form of the K-feldspar.

The observed distribution of the K-feldspar polymorphs could be explained in terms of partial superimposition of secondary variation on primary variation but it seems that none of the observations specifically require this condition. Indeed, if orthoclase was formed by incomplete transformation of the intermediate microcline during a reheating episode, it would have to take in sodium to account for its present apparent chemical composition. Besides which, it appears unlikely that intermediate microcline would be preserved during a reheating episode (Steiger and Hart, 1967).

The principal difference between the primary and the secondary variation models is the origin of the orthoclase. Both models rely on slow cooling and a sluggish transformation as the main factor in the production of the intermediate microcline. However, the broad correlation of rock type and distinctive potassium feldspar polymorphs is a strong argument for the variation being dominantly primary.

As pointed out previously the complex undoubtedly has a metamorphic texture and foliation. This foliation and recrystallisation could either have been formed closely synchronous with the intrusion of the complex or during a later period of deformation and reheating. It is interesting that in some samples from the Red granitic gneiss only shown to contain microcline the polygonal recrystallized areas must be microcline, whilst similar recrystallized areas in sample 516 from the "dark phase" cutting the Red granitic gneiss would seem to be orthoclase as no other phase was detected in this sample. Both rocks have suffered a similar deformational history as they are intimately related in the field and have a common foliation. This could be considered an indication that the recrystallization and deformation was closely synchronous with the formation of these rocks and the same conditions influenced the identity of the recrystallised areas as did the identity of the original crystals. If the recrystallized areas were evidence of first order transformations at a much later time then it would seem more likely that the same phase would have been formed in both the Red granitic gneiss and the "dark phase" on recrystallization under the conditions operating at that time.

In summary, there is a variation in the distribution of the structural states of the K-feldspar polymorphs in the Thiebot complex. Although not the only possible interpretation, this variation may be explained as primary variation originating in rocks of different bulk composition. It is suggested from the structural state of the K-feldspar polymorphs that deformation took place close to the time of intrusion and was followed by an extensive period of annealing and slow cooling without a major reheating episode.

The Chemistry of the Thiebot Complex

A number of samples were selected for analysis as being representative of the main rock types of the complex. The positions from which these were taken are shown on the sketch map (figure 3.3). The methods of analysis used for both major and trace element analyses are described in the Appendix.

The results for the major elements are given in table 3.5. Distinct groupings with compositional differences are apparent corresponding to the main rock types. The differences in the proportion present of almost every element in the main rock types are so striking that there can be no doubt that each has its own characteristic major element composition. These are summarised in the averages given below.

	Moulinet quartz dioritic gneiss (average of 2).	Thiebot granodioritic gneiss (average of 4)	Red granitic gneiss (average of 3)
SiO_2	58.0	67.4	73.8
TiO_2	0.85	0.48	0.15
Al_2O_3	17.49	16.07	13.83
Fe_2O_3	1.79	0.94	0.18
FeO	4.92	2.82	1.65
MnO	0.12	0.08	0.05
MgO	3.5	1.21	0.41
CaO	5.03	2.11	1.11
Na_2O	3.0	3.8	3.75
K_2O	3.07	3.04	4.11
P_2O_5	0.21	0.13	0.05
H_2O^+	1.80	1.2	0.76
	99.78	99.28	99.85

In passing from the Moulinet quartz dioritic gneiss to the Thiebot granodioritic gneiss and then to the Red granitic gneiss there is an increase in silica and a slight increase in total alkalis but there is a steady decrease in the amount of each of the other elements present including water.

The changes in composition with increasing silica content may also be shown on variation diagrams of the different components in terms of Niggli numbers plotted against Niggli Si (figure 3.5). All the Niggli numbers plotted tend to show rather regular variation, all decreasing with increasing Si with the exception of Niggli al and alk, which show increases, and k which shows rather irregular variation. The two samples from the Fontenelles granodioritic gneiss sometimes show slight deviations from this trend of regular variation.

On this and subsequent diagrams, analysed samples from the Jardeheu quartz dioritic gneiss have been plotted for comparison and comment will be made on their distribution in the section on the Jardeheu gneiss.

When the analyses are plotted on an AFM diagram (figure 3.6) they follow a calc - alkaline trend, showing little iron enrichment relative to magnesium in the earlier members. They have an alkali - lime index of about 57 (Peacock 1931) as shown in figure 3.6. On a triangular diagram of Na_2O - K_2O - CaO (figure 3.6) the samples show the type of trend expected from a calc - alkaline rock series but there is some scatter of the points. The rocks show no tendency towards enrichment in K_2O relative to Na_2O in the later members of the series as is often the case in other calc - alkaline series.

The results for the trace elements are shown in table 3.6. There is no extreme variation in the concentration of any element throughout the series, although Rb does show a slight increase and Sr a

TABLE 3.5

CHEMICAL ANALYSES OF ROCKS FROM THE THIEBOT COMPLEX

	Thiebot Granodioritic Gneiss				Red Granitic Gneiss				
	120	344	352	332	342*	341*	340	470	356
SiO_2	67.3	66.4	70.6	65.4	73.37	72.76	73.5	74.1	73.9
TiO_2	0.45	0.46	0.37	0.63	0.17	0.17	0.16	0.14	0.16
Al_2O_3	16.56	16.20	15.51	16.0	14.18	13.92	13.85	13.57	14.06
Fe_2O_3	1.06	0.79	0.17	1.76	0.0	0.0	0.23	0.15	0.15
FeO	2.91	3.27	2.43	2.67	2.27	2.21	1.68	1.61	1.66
MnO	0.09	0.09	0.05	0.08	0.04	0.04	0.05	0.04	0.05
MgO	1.19	1.26	0.85	1.53	0.67	0.67	0.42	0.40	0.42
CaO	2.85	2.68	0.75	2.17	0.47	0.97	1.57	0.91	0.84
Na_2O	3.8	4.3	3.67	3.43	3.98	3.83	3.50	4.04	3.70
K_2O	2.92	3.5	4.65	4.06	4.48	4.87	4.0	4.0	4.35
P_2O_5	0.13	0.13	0.11	0.14	0.07	0.07	0.05	0.05	0.05
H_2O^+	1.04	0.98	1.34	1.55	N.A.	N.A.	0.68	0.84	0.76
	100.3	100.06	100.5	99.42	99.70	99.51	99.69	99.85	100.1

	Dark phase	Fontenelles		Moulinet		Jardeheu Gneiss		
	516	9*	330*	325	4	472*	439*	J32
SiO_2	68.0	64.67	63.41	57.4	58.6	59.23	60.08	57.60
TiO_2	0.53	0.65	0.75	0.85	0.85	0.91	0.85	1.18
Al_2O_3	14.46	15.99	14.89	17.49	17.49	16.77	16.67	17.99
Fe_2O_3	0.93	1.76	2.05	1.57	2.0	1.19	1.11	1.00
FeO	3.46	2.95	3.59	5.12	4.73	4.96	4.87	4.97
MnO	0.10	0.08	0.09	0.12	0.12	0.07	0.07	0.14
MgO	1.09	2.24	3.26	3.5	3.5	4.03	3.71	2.84
CaO	2.28	2.62	3.70	5.55	4.52	6.66	6.16	7.42
Na_2O	3.52	3.47	3.21	3.0	3.0	3.54	3.67	3.77
K_2O	3.57	4.67	4.05	2.93	3.3	1.90	2.04	1.87
P_2O_5	0.14	0.29	0.33	0.21	0.21	0.37	0.35	0.46
H_2O^+	1.14	N.A.	N.A.	1.82	1.78	N.A.	N.A.	0.68
	99.22	99.39	99.33	99.56	100.1	99.63	99.58	99.92

* Determined by X-ray fluorescence.

N.A. Not analysed.

TABLE 3.6

TRACE ELEMENT ANALYSES (IN PPM) OF ROCKS FROM THE THIEBOT COMPLEX

	Moulinet		Thiebot granodioritic gneiss				Dark phase
	325	4	120	344	352	332	516
Rb	107	107	93	115	125	118	125
Ba	691	1503	1049	1373	1051	961	2360
Pb	8.6	12	13	11	8.8	13	12
Sr	521	505	384	417	246	387	390
La	32	30	33	48	45	55	94
Ce	53	57	50	83	73	62	146
Nd	36	35	36	33	37	45	54
Y	19	22	24	21	22	23	11
Th	3.9	4.6	7.2	6.6	13	12	14
U	1.6	2.2	1.8	2.8	5.1	4.6	2.5
Zr	137	150	204	210	190	311	215

Red granitic gneiss

	342	341	340	466	467	470	356
Rb	97	122	136	123	138	128	141
Ba	1903	890	1013	893	792	906	876
Pb	12	14	12	31	12	18	16
Sr	457	188	240	235	190	243	230
La	39	37	30	38	35	28	31
Ce	62	57	46	58	53	45	48
Nd	30	27	28	31	26	24	27
Y	15	16	13	19	14	13	17
Th	11	6.3	8.9	9.9	11	11	9.5
U	2.6	2.1	1.1	4.3	3.8	1.3	3.7
Zr	108	109	104	109	100	99	95

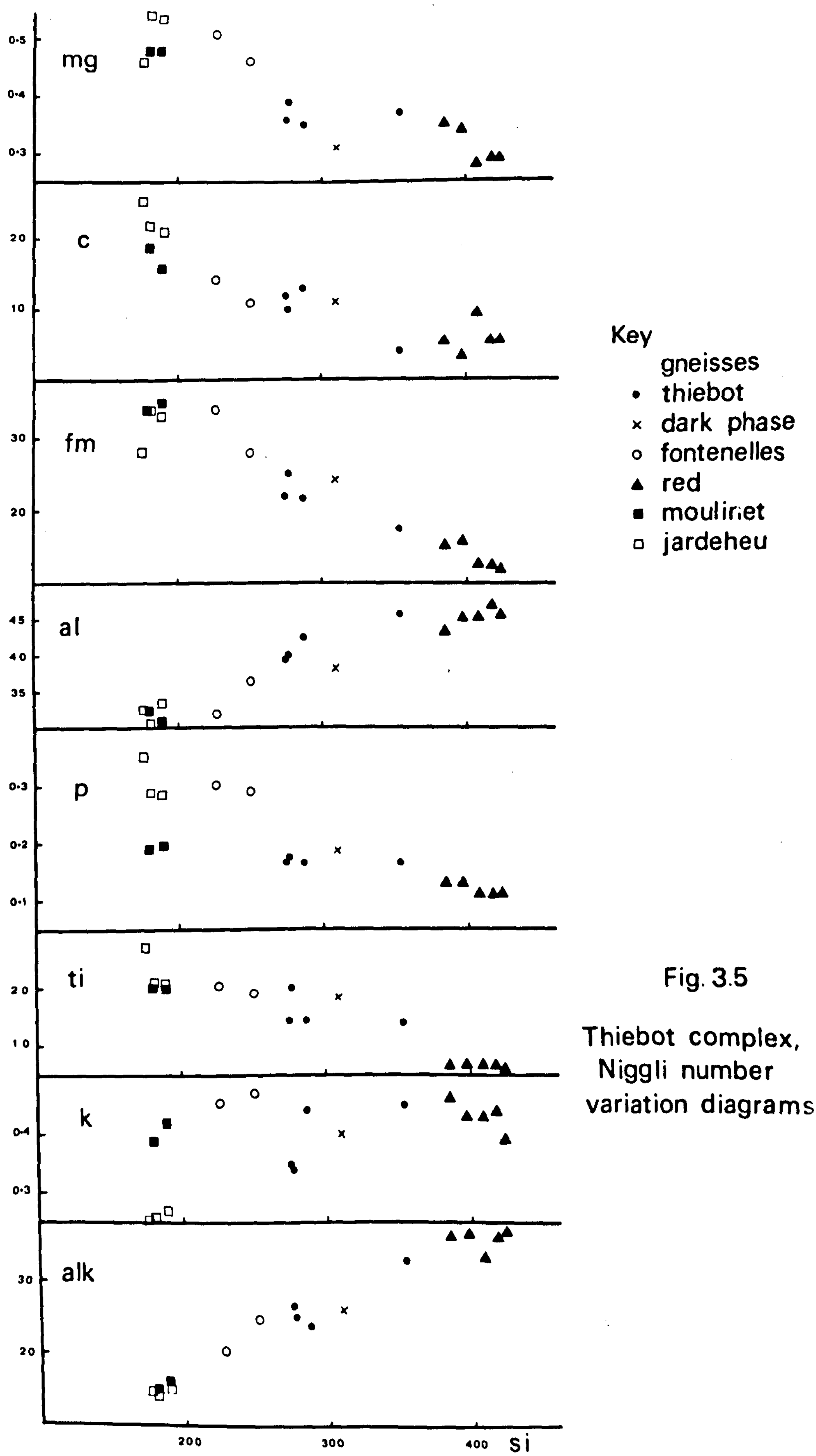
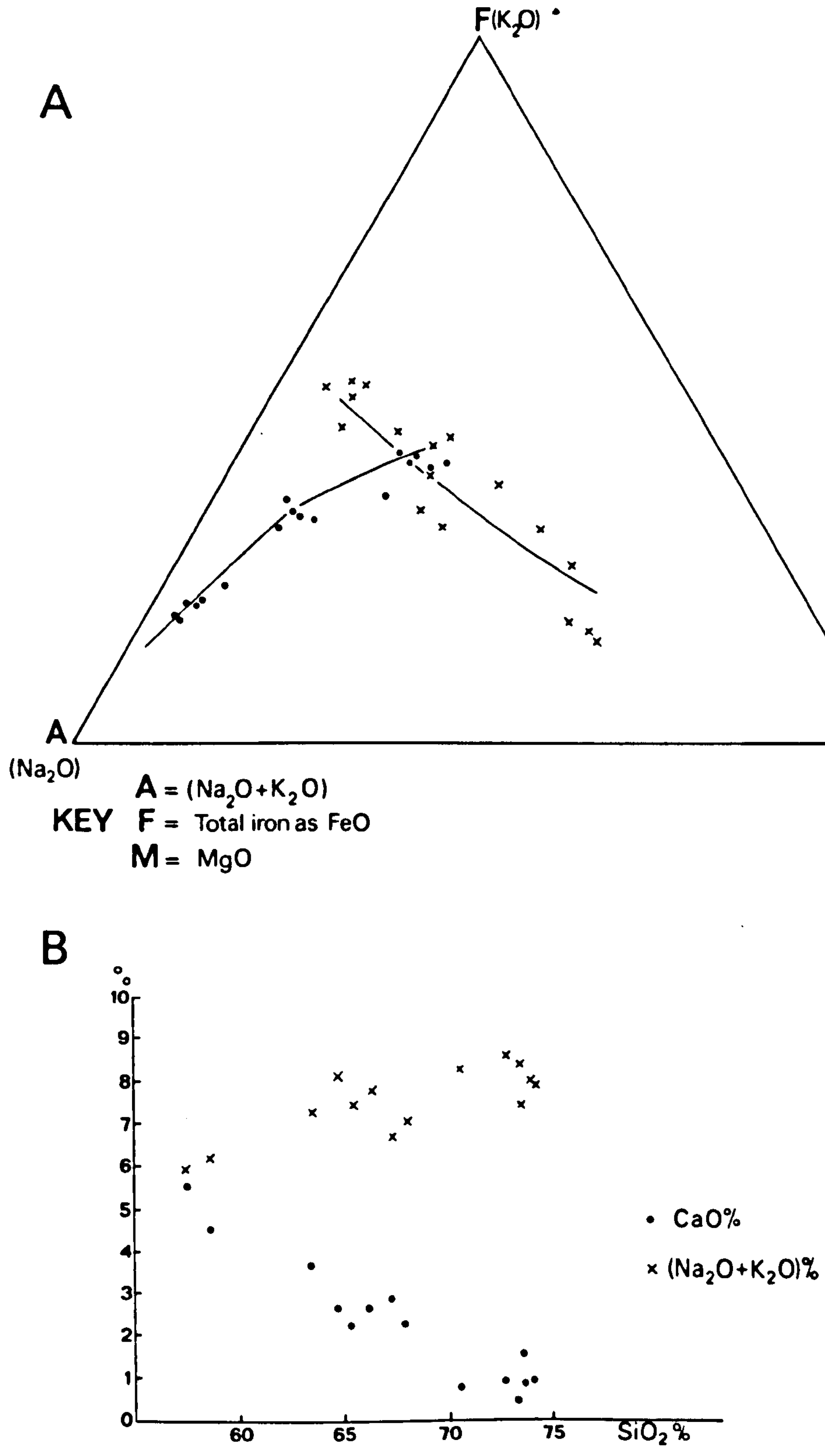


Fig. 3.5

Thiebot complex, Niggli number variation diagrams



Plot of CaO% and (K_2O+Na_2O)% against SiO_2%
Alkali-lime index (Peacock 1931) SiO_2 content at intersection of curves, about 57.

Fig. 3.6 Thiebot Complex

A. Combined AFM (•) and Na_2O-K_2O-CaO

B. Alkali-lime index plot (Peacock 1931) general decrease with increasing SiO_2. The Moulinet quartz dioritic gneiss may be distinguished from the other main rock types by its higher Sr and lower Th and U contents. The Thiebot granodioritic gneiss contains higher Zr than the other rock types. All the trace elements, with the exception of Ba, are within a reasonable range of the values given for an average granodiorite (Taylor, 1968). The concentration of Ba found is about double that quoted by Taylor (op. cit.) for an average granodiorite. This is not the result of a systematic analytical error. The values obtained for reference standards analysed at the same time were close to their recommended values. Also certain of the samples were analysed completely independently at the C.N.R.S., Nancy by emission spectroscopy and virtually identical results were obtained. However, more recent estimates of the abundance of Ba in granitic rocks, e.g. A.K. Fischer (1970) agree more closely with the average Ba value obtained here.

The major element chemistry of sample 515 from the "dark phase" cutting the Red granitic gneiss shows similarities to that of the Thiebot granodioritic gneiss. However, the trace element chemistry shows marked distinctive features unique amongst the rocks analysed. Ba, La, Ce, Nd and Th are all considerably higher in this rock sample than in any of the others.

Petrogenesis of the Thiebot Complex

The field relations and systematic variations in petrography and chemistry of the Moulinet quartz dioritic gneiss, Thiebot granodioritic gneiss and Red granitic gneiss suggest a close petrogenetic relationship between these rocks. Partial fusion in the crust has been suggested as a reasonable mechanism by which calc - alkaline rocks of this type may form. (Brown and Fyfe, 1970; Robertson and

Wyllie, 1971; Brown, 1973).

As most of the analysed rocks approach or exceed 80% normative Qz + Or + Ab + An, the Qz - Or - Ab - An - H_2O system may be used as an approximation to the system from which the rocks crystallized. As the rocks often contain the hydrous minerals biotite and hornblende, some water must have been present but as pegmatites and other indications of an abundant hydrous phase are absent they probably crystallized in water undersaturated conditions. When plotted in the Ab - An - Or - Qz tetrahedron the rocks form a trend which is similar to the trend recorded for calc - alkaline plutonic rocks of the Sierra Nevada batholith (Presnall and Bateman, 1973). The trend for the Thiebot complex rocks is shown projected onto the Ab - An - Or face of the tetrahedron in figure 3.7 with the Sierran trend, 'mn', superimposed. Presnall and Bateman show, from theoretical considerations, that the Sierran trend may be reasonably explained in terms of a single equilibrium fusion event from a lower crustal source, providing a crystal mush of partially melted material which subsequently underwent fractional crystallization at a higher crustal level. Regardless of the degree of separation of liquid from crystals all compositions would lie on the observed trend line assuming the composition of the lower crustal source region lies towards the basic end of the trend.

The Thiebot complex trend is essentially similar to the Sierran trend and the other observed features of the complex also appear to support a similar explanation for the origin of the complex. Thus the Moulinet quartz dioritic gneiss was the first fraction to crystallize from a contaminated crystal mush. This solid outer shell was then broken through by the remaining magma. Again the outer part crystallized, producing the Thiebot granodioritic gneiss and was

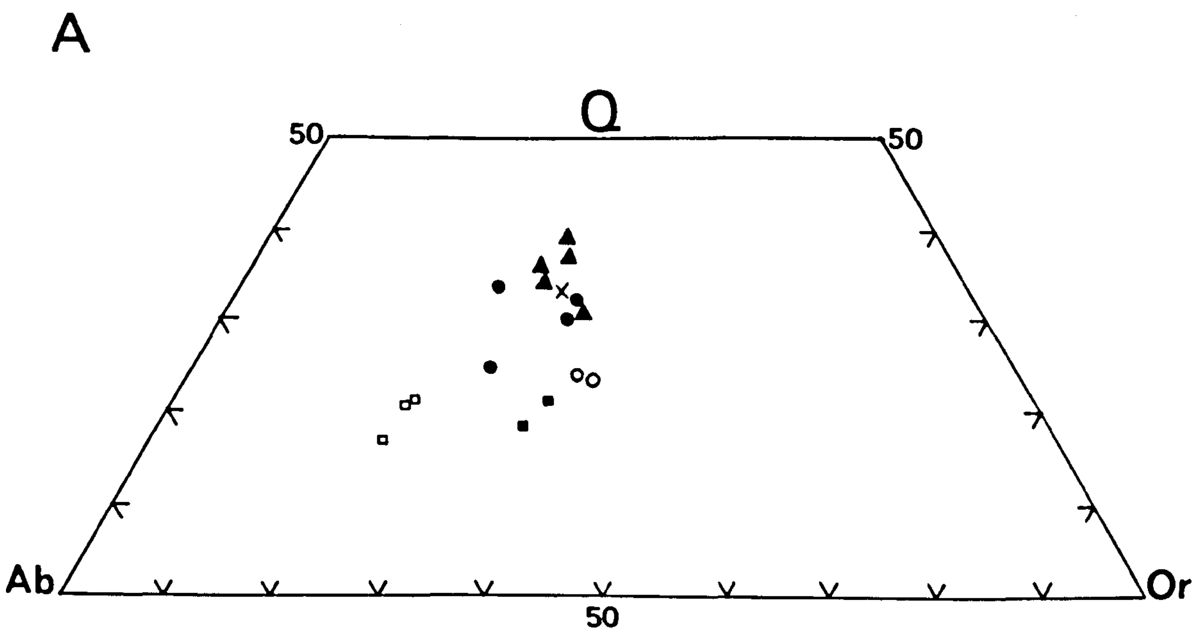
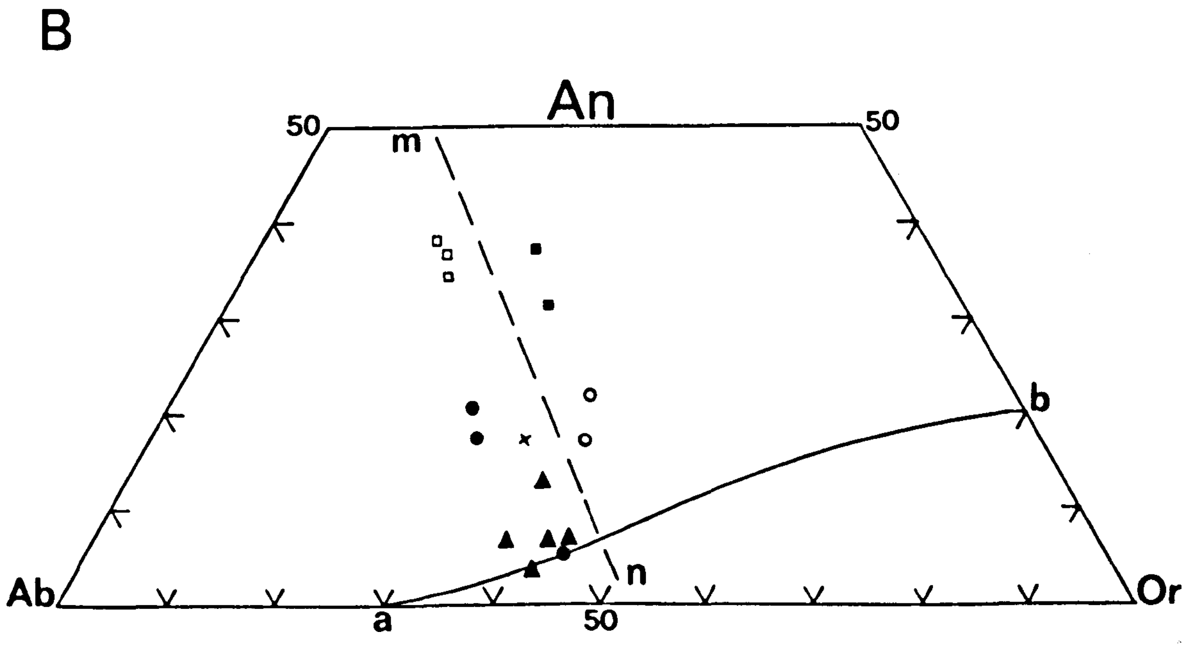


Fig.3.7 Thiebot complex

A. CIPW normative ternary components.

B. CIPW normative feldspar.



a-b, projection of quaternary univariant line, **m-n**, Sierra Nevadan Batholith trend.
Key as in figure 3.5.

followed by solidification of a largely uncontaminated liquid with a composition close to the quaternary univariant line in the Ab - An - Qz - Or system as the Red granitic gneiss. The Fontenelles granodioritic gneiss in terms of chemical composition always plots as the next member in the series after the Moulinet quartz dioritic gneiss yet field evidence shows it to be younger than the Thiebot granodioritic gneiss. It may represent intrusion of remnants of unfractionated material still uncrystallized from within the complex or, alternatively, late stage liquid similar to that which formed the Red granitic gneiss but here largely contaminated by Moulinet quartz dioritic gneiss.

The Moulinet quartz dioritic gneiss contains more hornblende and a more calcic plagioclase than the other members. Depending on the degree of partial fusion of the source region this plagioclase may be considered either as a residual phase or the result of later fractional crystallization. The complex zoning of the plagioclase and suggestions of resorption, particularly in the later members, may be an indication of repeated attempts to achieve equilibrium with the changing composition of the liquid phase. Both the Moulinet quartz dioritic gneiss and the Thiebot granodioritic gneiss contain dark xenoliths which may be interpreted as residual refactory material from the partial fusion carried up to higher crustal levels with the liquid phase. This refractory material may be the source of the higher zirconium content of the Thiebot granodioritic gneiss.

The initial strontium isotope ratio for the complex as determined by Leutwein et al. (1973) is 0.70705. This is too low to have been produced by the melting or metasomatism of average crustal materials and is slightly higher than expected for the upper mantle. The major Phanerozoic calc - alkaline batholiths of North America have similar intermediate initial strontium isotope ratios. These ratios could be the result of the production of granitic melts by partial melting of either lower crustal rocks with lower than average Rb/Sr ratios e.g. granulites, or mixtures of material of mantle origin and intermediate or upper crustal origin. At present no way of distinguishing between these two possibilities has been found. (Faure and Powell, 1972).

The Structure and Metamorphism of the Thiebot Complex

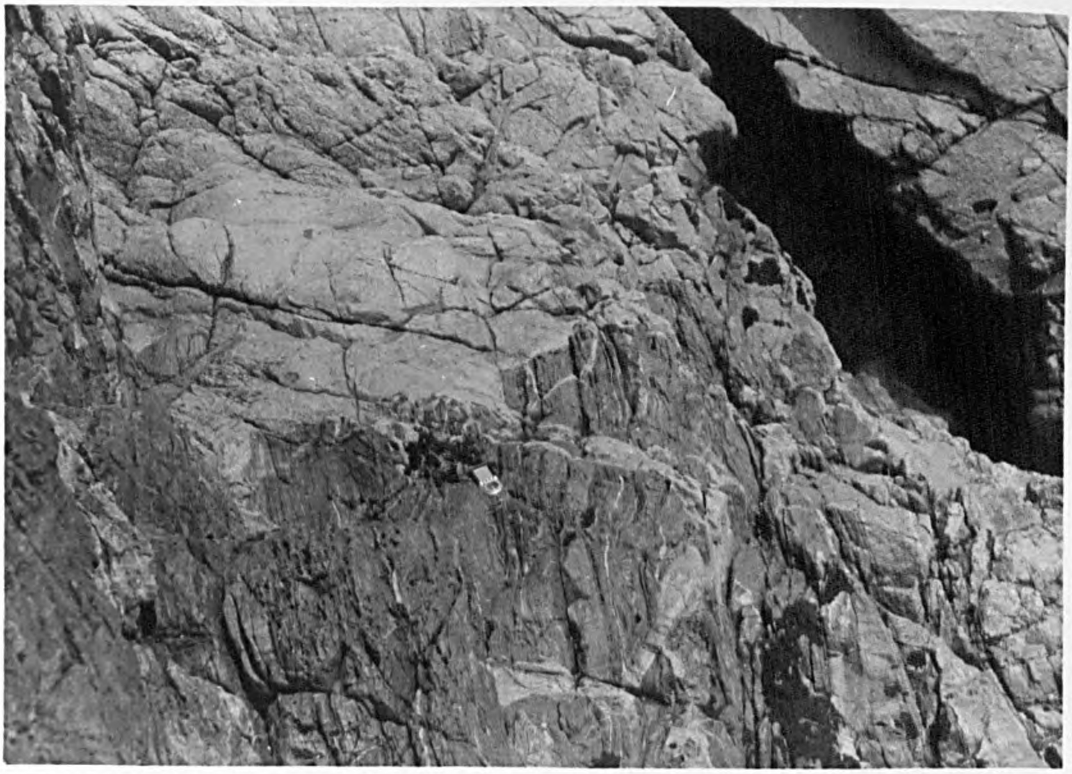
The Thiebot orthogneiss complex was intruded after the formation of the main foliation (S_2) in the Nez de Jobourg gneisses. No F_3 folds were found cross-cut by the contacts of the Thiebot gneisses and it is necessary to use indirect evidence to establish that there was a D_4 deformation. It is unlikely that the steeply dipping nearly N-S trending foliation in the Thiebot gneisses (figure 3.2) could have been formed by the same stress field required to produce the assymmetric F_3 folds. There are no dykes equivalent to the post-D_2 deformed dykes of the Nez de Jobourg gneisses in the Thiebot gneisses. This does suggest that the Thiebot gneisses are younger than these dykes. If the majority of these dykes are post D_3 then the Thiebot complex is likely to be post D_3 and its foliation produced by a D_4 deformation.

On the west side of Anse des Moulinets the edge of a screen of the Nez de Jobourg gneisses enclosed in the Moulinet quartz dioritic gneiss has been folded. The S_2 foliation is folded on almost vertical axes in a number of small folds, all of which have axial planes parallel to the foliation in the surrounding Moulinet quartz dioritic gneiss. It is just possible that these are F_4 folds. No other examples of this folding were found at any other localities.

The D_4 deformation has had little effect on the gneisses of the

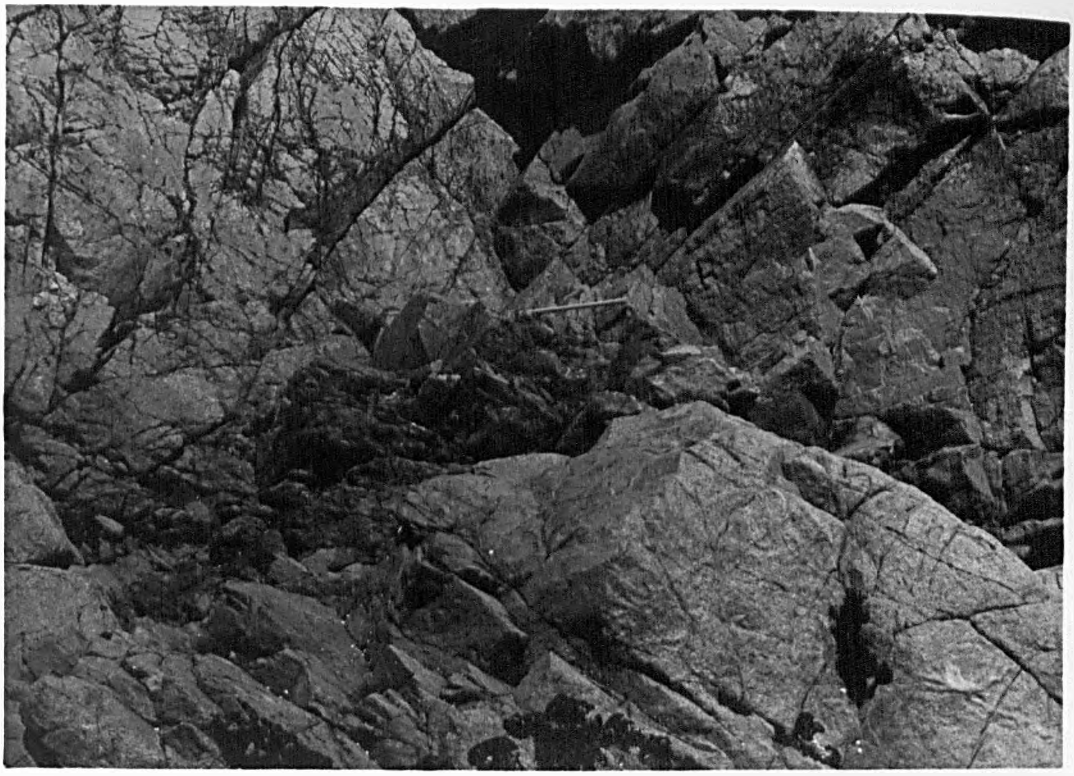
3.1 Thiebot granodioritic gneiss cross-cuts S_2 in gneisses of Nez de Jobourg area, Pointe du Bec de l'Ane.

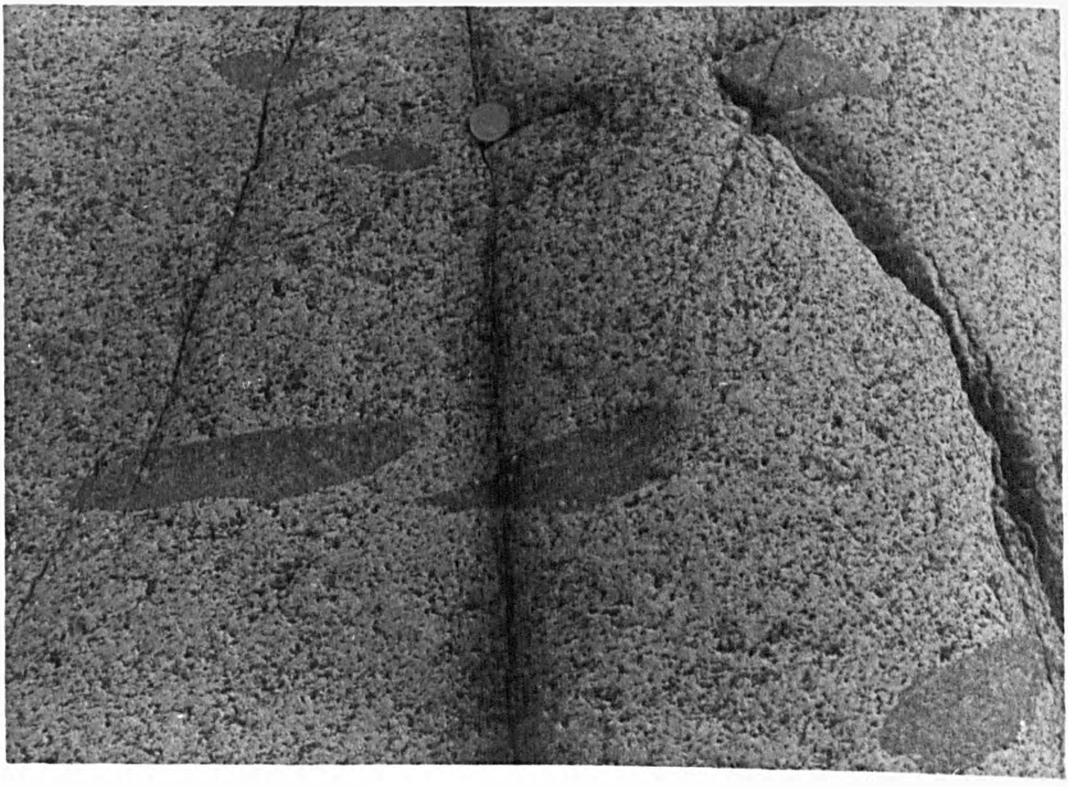
3.2 Close up of contact of plate 3.1.



3.3 Basic dyke, below hammer, truncated by contact of Thiebot granodioritic gneiss, Pointe du Bec de l'Ane.

3.4 Xenoliths in Thiebot granodioritic gneiss.





CHAPTER 4

THE GNEISSES OF THE OMONVILLE AREA

An area of gneisses occurs on the north coast of La Hague around the village of Omonville-la-Rouge. To the west of Pointe Jardeheu they have been intruded by the St. Martin monzonite and in the east at Pointe d'Etimbert they are overlain by Cambrian conglomerates and arkoses. Inland the exposure is limited but is sufficient to define the extent of the gneisses (see end maps 1 and 5).

The sequence consists of banded gneisses and K-feldspar augen gneisses with associated deformed basic dykes. The gneisses are cut by a quartz dioritic gneiss at Pointe Jardeheu which bears a striking resemblance to the Moulinet quartz dioritic gneiss of the Thiebot complex. All these rocks have been intruded by granitic bodies with a gneissose foliation.

Although the rock types and sequence of events differ in detail from those of the gneisses of the Nez de Jobourg area there are sufficient general similarities to enable a correlation to be made between the gneisses of the two areas. The gneisses may be broadly similar in age as samples from both areas fall on the same general isochron (Leutwein et al., 1973). The gneisses of the Omonville and Gréville areas may have been part of the same series. However, they are considered separately because of their actual separation by overlying Cambrian sediments and the presence of a large fault between them.

A sequence of events for the rocks of the Omonville area is given in table 4.1 and the gneisses will be described as far as possible in this order.

TABLE 4.1

SEQUENCE OF EVENTS IN THE GNEISSES OF THE OMONVILLE AREA

Event	Evidence
Sedimentation and formation S_0.	Inclusions semi-pelite.
Basic lavas or dykes.	Amphibolitic inclusions.
D_1 deformation and production of banding.	No F_1 folds found. Obvious banding S_1, now transposed parallel to S_2 and forming F_2 fold hinges.
M_1 metamorphism.	Quartz-feldspar banding suggests amphibolite facies.
D_2 deformation producing S_2 foliation and banding and F_2 folds	S_2 now main foliation, F_2 small scale fold hinges. Intersection S_1 and S_2 forms strong lineation L_2.
M_2 metamorphism.	Amphibolite facies mineral assemblages.
Intrusion of basic dykes.	Now deformed dykes, cut S_2 but foliated.
? D_3 deformation producing late kinks.	Small scale folding of S_2 but no other evidence of place in sequence of events.

TABLE 4.1
(Continued)

SEQUENCE OF EVENTS IN THE GNEISSES OF THE OMONVILLE AREA.

Event	Evidence
Intrusion of quartz diorite.	Jardeheu quartz dioritic gneiss. Contact cross-cuts S_2.
D_4 deformation production of S_4 foliation.	S_4 foliation in Jardeheu gneiss.
Intrusion of granite sheets	Omonville streaky gneiss bodies cross-cut S_4 foliation.
D_5 deformation, production of S_5 foliation.	S_5 foliation only in streaky gneiss.
? Metamorphism M_3.	Post D_2 dykes show assemblage hornblende + plagioclase. Metamorphism possibly syn-D_4?
Retrogressive metamorphism M_4	Most gneisses including Jardeheu gneiss show some retrograde minerals.

Inclusions in the Gneisses of the Omonville Area

The gneisses contain a variety of amphibolitic and semi-pelitic inclusions usually elongate and about 1 m in length, although in one locality at La Foireuse an area of amphibolite more than 20 m in length is found enclosed in the gneiss (see plate 4.1). Good examples of these inclusions may be found in the section between Port d'Omonville and le Fort. They are similar in nature to the inclusions in the gneisses of the Nez de Jobourg area.

Semi-pelitic inclusions

The semi-pelitic inclusions found are all fairly uniform in appearance and composition. They are enclosed by the main foliation of the gneiss and their long axes lie in the plane of this foliation. Most have a well developed foliation and a fine scale lamination of more biotite rich and more leucocratic lamellae. Some also show this variation with a larger scale banding.

They are fine grained and usually have the mineral assemblage, quartz + plagioclase + biotite + magnetite. Plagioclase is often extremely altered and surrounded by elongate areas of quartz containing many small grains separated by complex crenulate boundaries. Biotite, α : yellow, β , γ : brown forms flakes 0.1 mm in size often in aggregates associated with magnetite. One inclusions with more abundant biotite forming bands of flakes up to 1 mm in size contains garnet + epidote + chlorite in addition to the usual mineral assemblage. The garnet is developed as euhedral 0.1 mm grains in pseudomorphic aggregates of mica and clay minerals within the biotite layers and is now partially retrogressed to chlorite. Chlorite is also developed along the cleavages in the biotite. Epidote occurs as well formed isolated prisms up to 0.4 mm long growing in the biotite bands.

This rock with its more pelitic nature is more sensitive to changing metamorphic conditions. The original banding was formed at an early stage together with the mineral now only present as pseudomorphs. During a second metamorphic episode the banding was enhanced and the garnet developed. A later retrograde metamorphism gave rise to the epidote and partial development of chlorite.

As in the gneisses of the Nez de Jobourg area the semi-pelitic inclusions are interpreted as remnants of a series of sediments predating the gneisses and from which, at least in part, the gneisses were formed.

Amphibolitic inclusions

A variety of amphibolites differing in the details of their textures and mineralogy may be distinguished. The largest mass of amphibolite at La Foireuse is dark in colour and massive. It is strongly banded with 1 mm wide layers of hornblende and of plagioclase with quartz. It contains hornblende + plagioclase + quartz + garnet + magnetite + biotite. Hornblende, α : yellow, β : green, γ : dark green and $\gamma : c = 19^{\circ}$ is abundant and occurs mainly in bands as prisms up to 1 mm in size but is also found in the more felsic layers forming poikiloblastic crystals enclosing plagioclase and garnet. Magnetite with an elaborate almost frilly habit is found enclosed in hornblende and is sometimes closely associated with chlorite. Rarely the hornblende is partly replaced by brown biotite. The plagioclase and quartz bands contain anhedral plagioclase (An_{10}) with fine scale albite twinning and abundant antiperthitic intergrowths of K-feldspar. Quartz is subordinate and forms equidimensional grains less than 0.3 mm in size. The felsic bands also contain the garnet as 0.1 mm equidimensional granules often forming continuous layers within the bands and with no obvious signs of retrogression. Other amphibolitic inclusions show similar strongly developed banding and a similar mineral assemblage but are characterised by abundant granules of zircon occurring in the plagioclase and sometimes in the hornblende.

One amphibolitic inclusion collected from the Baie de Jardeheu was actually enclosed in the St. Martin monzonite although it quite obviously was derived from the gneisses. It shows strong compositional banding with all the minerals forming parallel bands but was particularly characterised by the mineral assemblage, hornblende + pyroxene + plagioclase + quartz + magnetite + sphene. Hornblende, α : pale yellow, β : light green, γ : green and $\gamma : c = 16^{\circ}$ is often poikiloblastic with crenulate margins and includes quartz, plagioclase and pyroxene. The plagioclase is fairly abundant and is oligoclase (An_{16}) in composition. The pyroxene occurs as stubby euhedral crystals up to 0.4 mm in size although some grains are very much smaller. It also occurs as skeletal remnants enclosing quartz and plagioclase and with hornblende growing on it. The pyroxene is colourless, has a low birefringence, moderate 2V and an extinction angle $\gamma : c = 40^{\circ}$ and is probably augite.

A distinctive amphibolitic inclusion from La Foireuse contains abundant porphyroblasts of plagioclase about 5 mm in diameter giving the rock a spotted appearance. In thin section this plagioclase may be seen to be extremely altered to white mica and to enclose chlorite and epidote and radially arranged acicular hornblende. The porphyroblasts are surrounded by an intergrowth of hornblende, α : yellow, β : light green, γ : green and $\gamma : c = 17^{\circ}$. This hornblende contains inclusions of clear quartz and granules of magnetite and is overgrown by chlorite.

The amphibolitic inclusions may possibly represent the remnants of a number of different basic igneous events in the early history of the gneisses. They certainly pre-date the formation of the main foliation in the gneisses and some may be much earlier than this event.

The Banded Gneisses

The banded gneisses and K-feldspar augen gneisses have not been mapped as separated units. However, there is a tendency for the banded gneisses to be more common in the bay to the east of Pointe Jardeheu and the K-feldspar augen gneisses to be more common around Omonville-la-Rogue. The banded gneisses are composite in appearance being made up of more felsic and more mafic units up to 50 cm in thickness (see plate 4.2). The more felsic bands often weather to a characteristic yellow colour. Sometimes a much finer lamination is developed and the greenish gneiss shows thin yellow felsic bands a few millimetres thick. In places the gneiss appears more acidic and has a much more flaggy appearance. The banded gneisses would seem to have been derived from a series of sediments together with associated basic bodies.

In thin section the gneisses are inequigranular with a maximum grain size of about 2 mm and have a mineral assemblage of quartz + plagioclase + biotite + magnetite $\pm$ hornblende $\pm$ chlorite $\pm$ muscovite. Quartz occurs as fairly equidimensional grains with regular boundaries and little sign of strain and has probably recrystallized. Plagioclase shows slight dimensional orientation parallel to the banding and is oligoclase (An_{13}) in composition. It is often extremely altered and may be overgrown by flakes of muscovite. Biotite, α: pale yellow, β, γ: brown or green is fine grained (0.1-0.2 mm) and forms aggregates around plagioclase grain boundaries. It may be replaced by chlorite and muscovite. Hornblende only occurs rarely in stubby dark green crystals. Accessory minerals may include zircon, apatite and magnetite.

The K-feldspar Augen Gneiss

K-feldspar augen gneiss occurs in parts of the Omonville area, for example at La Foireuse, Port d'Omonville and Baie des Fontenelles. A strongly discontinuous felsic banding is developed in these gneisses and this gives rise to a prominent lineation where it intersects the plane of the main foliation. The K-feldspar augen vary from abundant to sparse from place to place. In Baie des Fontenelles a well foliated red augen gneiss contain K-feldspar augen up to 3 or 4 cm in size and also shows pegmatitic veins about 5 cm wide containing K-feldspar cutting across the foliation.

The mineral assemblage found in these gneisses is quartz + plagioclase + K-feldspar + biotite although some samples also show the later growth of chlorite + muscovite + epidote. There is a variation in the intensity of the development of the banding. Some samples simply show a medium grained granitic texture whilst others have strong compositional banding. Plagioclase forms slightly elongate grains about 1 mm in size and is oligoclase (An_{14}) in composition. Bands of quartz contain grains usually less than 0.5 mm in size with crenulate margins and undulose extinction. Small flakes (0.1-0.2 mm) of biotite, α: yellow, β, γ: brown, are randomly arranged within elongate aggregates or occur around the margins of plagioclase grains. K-feldspar, usually up to 5 mm in size, is microcline perthite with prominent cross-hatch twinning. It is augen shaped and has inclusions of quartz and plagioclase. The margins are sometimes surrounded by a rim of myrmekite. Extinction is often shadowy and the grains appear to have been deformed. It is considered unlikely that any of the K-feldspar is later than the foliation.

Within the K-feldspar augen gneisses elongate bodies about 50 cm wide and varying in length up to several metres may sometimes be distinguished, for example on the beach at Omonville-la-Rogue. The field relations of these bodies is difficult to interpret. They appear to be ghostly relics of some earlier compositional variation in the gneiss rather than a distinct dyke phase. However, they seem to cross-cut the main foliation and banding in the gneiss and also to have a faint foliation themselves. They are fine grained (0.1-0.5 mm) and show the mineral assemblage, quartz + plagioclase + biotite + hornblende + chlorite. Quartz and plagioclase are the main minerals and biotite is much more common than hornblende. Plagioclase is oligoclase (An_{12}) in composition and is intergrown with biotite, α: yellow, β, γ: brown which has a random orientation in small (0.3 mm) flakes. The relatively minor hornblende, α: yellow, β: light green, γ: blue green and γ: c = 18° occurs as subhedral prisms often associated with the biotite.

<u>The Deformed Basic Dykes</u>

As in the Nez de Jobourg area basic dykes are found which clearly cross-cut the main foliation in the gneisses but have subsequently been deformed. They have a mineral assemblage of hornblende + plagioclase together with later epidote + chlorite + sericite and may be correlated with the post-D_2, pre-D_4 dykes in the Nez de Jobourg area. They may be shown to be truncated by sheets of the Omonville streaky gneiss.

In addition, a suite of basic dykes may be recognised, particularly in Baie des Fontenelles, that show strongly sheared margins and a cruder foliation in their central portions. Similar dykes cut the quartz dioritic gneiss at Pointe Jardeheu. In thin section they are seen to contain plagioclase + hornblende together with later chlorite + calcite + epidote but the plagioclase shows abundant evidence of relict igneous textures and it seems likely that these dykes post-date the D_4 deformation.

The Structural and Metamorphic Evolution of the Gneisses

Although the banded gneisses were almost certainly derived from a series of sediments there are no structures preserved that may be confidently assigned to this period of their evolution. The prominent felsic banding particularly in the K-feldspar augen gneisses pre-dates the formation of the main foliation. In keeping with the terminology used for the Nez de Jobourg area this banding is termed S_1 as there is no evidence that it was formed other than at the same time as the S_1 banding in the Nez de Jobourg gneisses. It is assumed that it was formed during a deformation D_1. The S_1 banding was folded by the D_2 deformation as may be detected by the presence of small scale F_2 fold hinges formed from the felsic banding lying within the main foliation (S_2). Again this deformation is considered to be equivalent to the D_2 deformation in the Nez de Jobourg area.

The main foliation (S_2) has a fairly consistent north-east strike throughout the area and shows an average dip of about 60°E although the angle varies between 80° and 45°E. The F_2 fold axes plunge SSW at about 40°, and intersections of the S_1 banding and the S_2 surface which form the L_2 lineations have a similar orientation (see figure 4.1A).

Apart from the variation in dip of the S_2 foliation which it was not possible to relate to actual fold hinges deformation subsequent to the D_2 deformation appears to have had relatively minor effects on the gneisses of the Omonville area. The main foliation has been deformed to give rise to a series of late kinks. These may be seen particularly clearly in the region of La Foireuse. They are small scale structures usually of the order of 10 to 20 cm in size. They have one short central limb bent at a high angle to the other longer

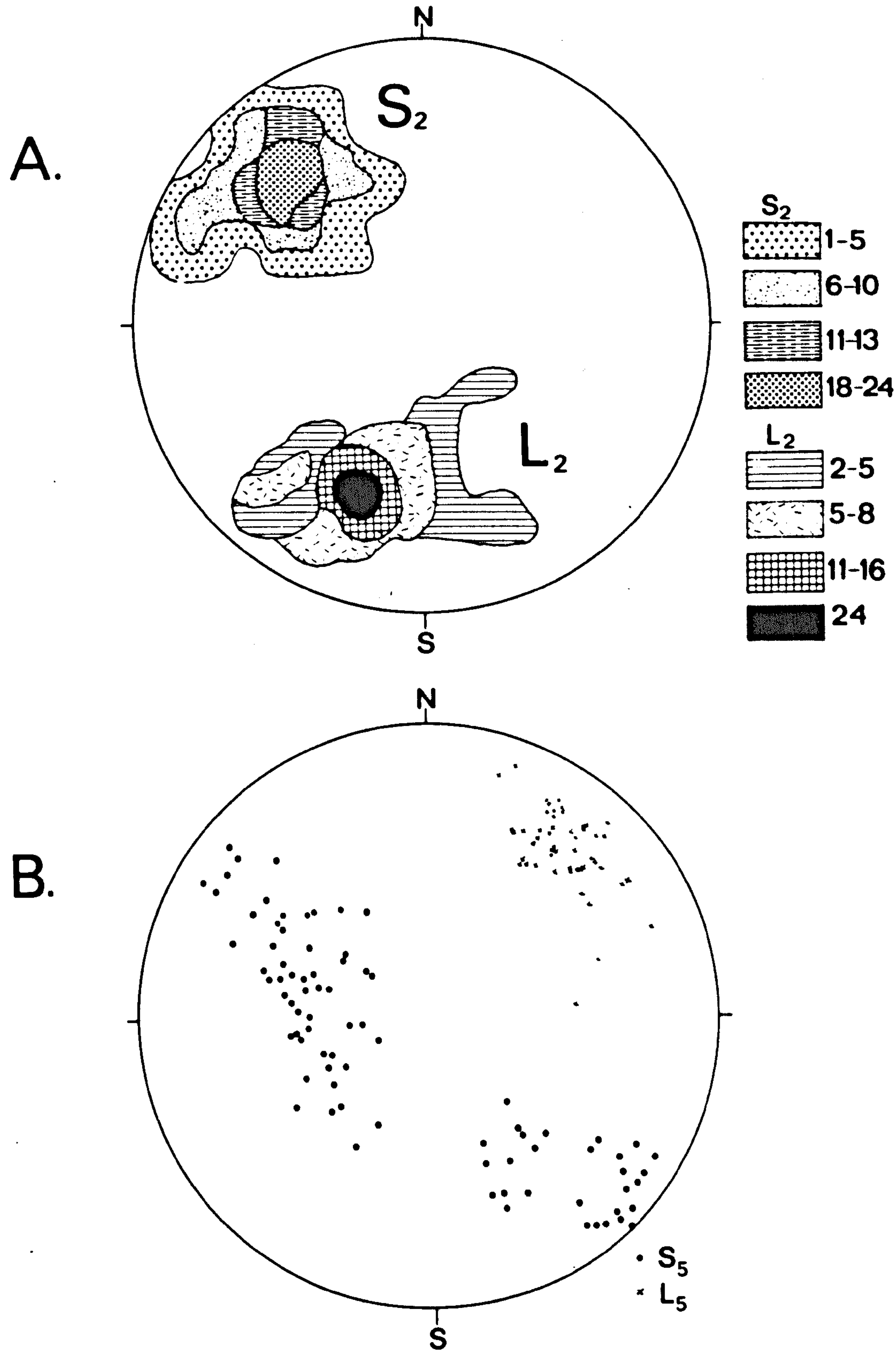


Fig.4.1.

A. 105 poles to S_2 126 L_2 lineations.

B. Omonville streaky gneiss. 87 poles to S_5 lineations.

limbs. The fold axes plunge steeply and the axial surfaces dip steeply and strike about 80°E of N. A shear zone often develops parallel to the axial surface and the short limb may be disrupted and slightly displaced. These folds may be equivalent to the F_3 folds of the Nez de Jobourg area as there are no other structures in the Omonville area which could be considered equivalent. If they are then there is a swing in the strike of the axial surfaces from around 20°E of N in the Nez de Jobourg area to around 80°E of N at Omonville. However, there is no real means of equating these structures in the two areas and the question may not be resolved further. The deformed basic dykes also provide some evidence for a period of deformation later than D_2 but prior to the intrusion of the Omonville streaky gneiss. Discussion of the foliation in the Jardeheu quartz dioritic gneiss and the Omonville streaky gneiss will follow the section describing them.

The metamorphic history of the gneisses of the Omonville area may only be established in rather general terms although there is no reason to suppose it was very different than that for the Nez de Jobourg area. There is evidence from the mineral assemblages detailed in the preceding sections for a period of amphibolite facies metamorphism. The hornblende + plagioclase assemblage in the deformed basic dykes suggests a further metamorphic event later than the formation of the S_2 foliation and there is abundant evidence for a later retrogressive metamorphism in the mineral assemblages suah as chlorite + epidote + calcite. It is not possible to be specific about the timing of this retrogressive phase.

The Jardeheu Quartz Dioritic Gneiss

The Jardeheu quartz dioritic gneiss is confined to Pointe Jardeheu and Baie de la Rivière. On the east side of Pointe Jardeheu it may be clearly seen to cross-cut the older gneisses of the area but it will be considered in this chapter as will the Omonville streaky gneiss. It is a medium grained fairly massive grey weathering rock in which rounded, hornblende rich, dark inclusions are fairly common. It has a foliation defined mainly by the alignment of biotite and hornblende. This foliation strikes about 60°E of N and dips 80°S.

The quartz dioritic gneiss is an inequigranular rock composed of a mosaic of plagioclase and subsidiary interstitial quartz together with aggregates of subhedral hornblende and biotite. Sphene is a characteristic accessory mineral. Plagioclase (about 56%) is andesine in composition (An_{36}-An_{40}). It occurs as subhedral grains 1-2 mm in size. Twinning is variable, but often thin continuous albite lamellae are prominent. Carlsbad and pericline twinning also occur and some continuous zoning is present. Hornblende (10-20%), α : pale brown, β : light green, γ : green and γ : $c = 19^{\circ}$ occurs as rather ragged grains 1-2 mm in size varying in shape from rounded to prismatic. Often several grains are grouped together with flakes of biotite surrounding them. Inclusions of quartz, apatite, sphene and magnetite are fairly common. Biotite (6-16%) is seen as elongate flakes reaching 2 mm in length. It is pleochroic from α : light golden to γ =dark brown. The flakes often have a striped appearance with the alteration of the biotite to green chlorite along the cleavage. Prehnite is sometimes seen growing along the biotite cleavage. Quartz (about 18%) may occur in patches 1-2 mm in size but is more commonly developed in the interstices between the other minerals. Sphene occurs as anhedral grains up to 1 mm in size often associated with magnetite but may also be seen as euhedral lozenge shaped crystals up to 1.5 mm long.

The Jardeheu and Moulinet quartz dioritic gneisses have many close similarities. Their texture and mineralogical composition are virtually identical as may be seen from their modal analyses (Table 3.2

TABLE 4.2

MODAL AND CHEMICAL ANALYSES OF ROCKS FROM THE JARDEHEU QUARTZ DIORITIC GNEISS

	472	177	439	180
Quartz	17.2	13.8	18.2	17.8
Plagioclase	52.4	56.9	57.0	57.3
K-feldspar	-	-	-	-
Hornblende	12.5	19.9	10.5	15.4
Biotite	16.3	5.6	13.2	5.6
Chlorite	0.2	1.5	0.2	2.9
Ore	0.5	0.7	0.3	0.1
Sphene	0.2	1.3	-	0.5
Others	0.7	0.3	-	0.2
Q	24.7	19.5	24.2	23.7
P	75.3	80.5	75.8	76.3
A	0	0	0	0
F	100	100	100	100
M	30.4	29.3	24.9	24.7
Counts	3661	1727	3751	3432

	472	439	J32
SiO_2	59.23	60.08	57.60
TiO_2	0.91	0.85	1.18
Al_2O_3	16.77	16.67	17.99
Fe_2O_3	1.19	1.11	1.00
FeO	4.96	4.87	4.97
MnO	0.07	0.07	0.14
MgO	4.03	3.71	2.84
CaO	6.66	6.16	7.42
Na_2O	3.54	3.67	3.77
K_2O	1.90	2.04	1.87
P_2O_5	0.37	0.35	0.46
H_2O^+	N.A.	N.A.	0.68
	99.63	99.58	99.92

472, 439 determined by X-ray fluorescence.
J32 from Jérémine (1930).

and Table 4.2). They are very similar chemically and the analyses for the Jardeheu rocks were included in the tables and diagrams for the Thiebot complex to illustrate this similarity. Perhaps most important of all, both have a similar structural setting. They both post-date the S_2 foliation in the nearby older gneisses and yet contain a nearly vertical foliation approximately parallel to S_2. On the basis of the above evidence it would seem reasonable to consider them both to have originated from the same intrusive phase. If this is so then the foliation in the Jardeheu quartz dioritic gneiss is equivalent to the S_4 foliation in the Thiebot complex. There is a difference in the strike of this foliation from nearly N-S in the Thiebot complex to 60°E of N at Pointe Jardeheu.

The Omonville Streaky Gneisses

The Omonville streaky gneisses are a characteristic feature of the Omonville area. Where they are well exposed along the coast they vary from bodies less than 20 sq m in area to larger bodies at least 1500 sq m in outcrop. In all they may occupy something like thirty per cent of the surface outcrop. They are medium to fine grained granitic rocks which cross-cut both the S_2 foliation in the banded and augen gneisses (see plate 4.2) and the S_4 foliation in the Jardeheu quartz dioritic gneiss (see plate 4.3). They may be massive and unfoliated, or have an obvious foliation defined by thin mafic bands which give the rock a streaky appearance. The variation in the orientation of this foliation and associated lineation will be described further later. Within the Jardeheu quartz dioritic gneiss the bodies tend to take the form of sheets gently dipping in a general easterly direction but this tendency is not so apparent elsewhere. Within some of the larger bodies rafts of banded and augen gneisses may be found. These do not appear to have been displaced far or

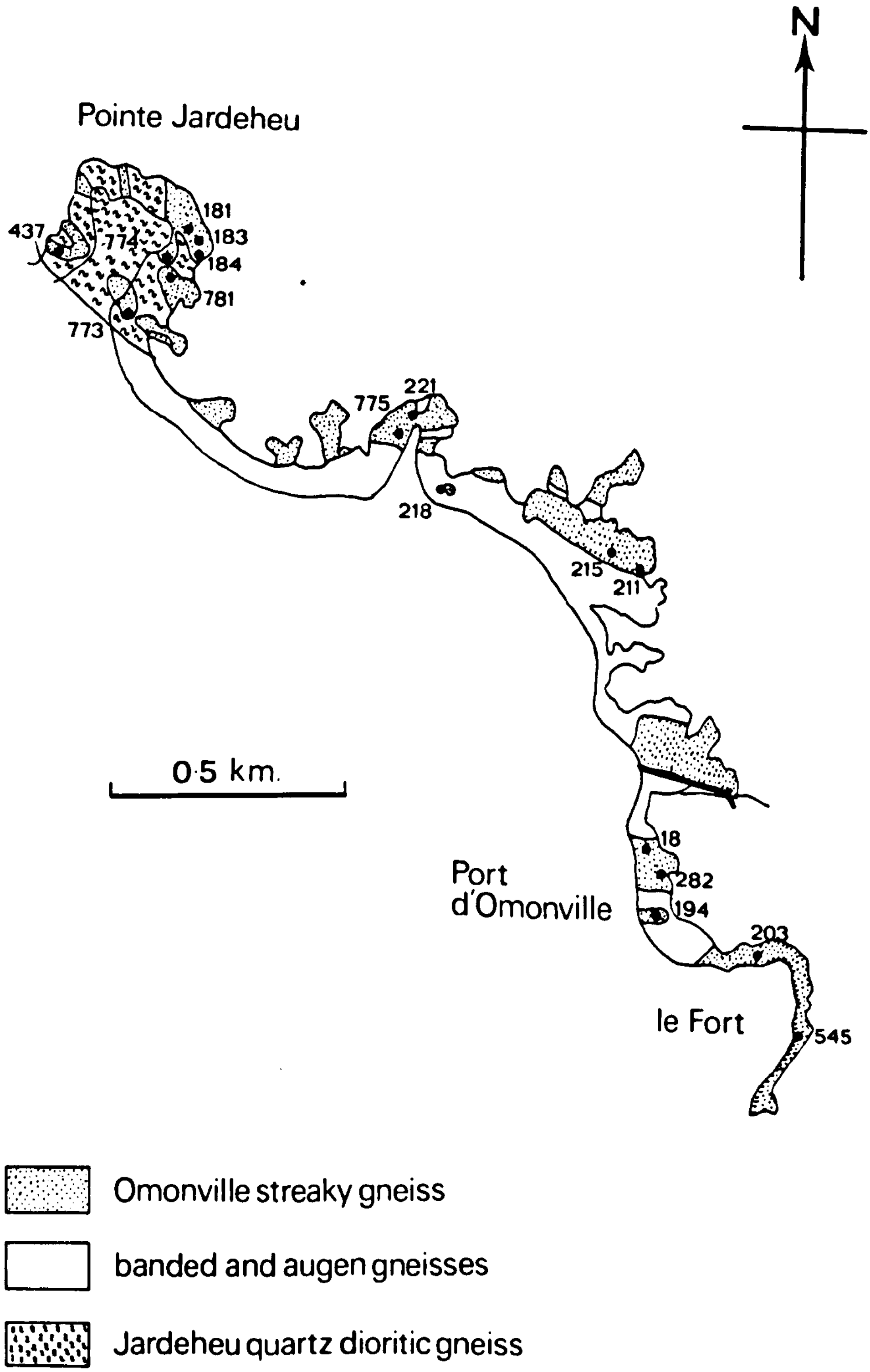


Fig. 4.2

Omonville streaky gneiss, sketch map of sample localities.

rotated as the S_2 foliation within them still retains the same orientation as that in the nearby gneisses.

The Omonville streaky gneiss normally forms a brown weathering medium grained rock with noticeable small porphyritic white plagioclases and thin streaks of mafic minerals. However, this appearance may vary depending on the degree of development of the foliation and the relative proportions of the constituent minerals. On the east side of Pointe Jardeheu the margins of some of the intrusive sheets are much darker in colour than the rest of the body. This is not a simple relationship, the thickness of the dark margin may vary up to several metres in places and intimate intertonguing of the darker and more usual material may be observed (see plate 4.4). The dark margin is not finer in grain sizenor does either variety appear to chill against the other. The darker variety is also encountered in the intrusive sheet forming the promontory on the east side of Baie de la Rivière. Here, however, it is rather lighter in colour with a mottled appearance arising from the more obvious white plagioclase phenocrysts and intergrown abundant mafic patches.

In thin section these dark rocks are seen to contain the mineral assemblage, plagioclase + quartz + hornblende + biotite + K-feldspar + chlorite. Plagioclase is the dominant constituent and forms euhedral phenocrysts between which finer grained quartz, plagioclase and K-feldspar occur (see plate 4.6). The foliation is defined by some fine scale compositional banding in this interstitial material and by streaks of biotite and hornblende. Plagioclase (45-55%) is normally about 2 mm in grain size but may rarely be as large as 5 mm. The phenocrysts are often euhedral and most of the central area has been replaced by cloudy alteration products although a clear rim is always visible. In a few instances the composition of the central area could be determined as andesine (An_{35}) whilst the clear rim varies from oligoclase (An_{15}) to albite (An_8).

Hornblende is variable in abundance but may make up about 10% of the rock. It occurs as larger subhedral grains commonly up to 1 mm in size, although exceptionally they may reach 4 mm long, with a pleochroic scheme, α : pale brown, β : green, γ : dark green or brown and γ : $c = 19^{\circ}$. They may show simple twinning and are commonly rimmed by biotite, α : golden yellow, β , γ : dark brown in small flakes growing into the hornblende. In addition hornblende with a distinctive pleochroic scheme, α : light brown, β : light green, γ : blue green may be seen to replace the margins of the larger grains of brown hornblende and to form elongate aggregates of small grains with biotite and magnetite.

The plagioclase phenocrysts, sometimes together with hornblende, tend to form clumps of several grains aggregated together. The interstitial areas around these aggregates contain fine grained (0.2 mm) quartz, plagioclase and K-feldspar. This may show bands of K-feldspar one grain thick and discontinuous bands of slightly elongate single quartz grains. The banding is accentuated by fine grained biotite and specks of opaque minerals and tends to be displaced around the phenocrysts. The proportion of fine grained groundmass material is low in the dark rocks and some samples contain none at all.

The darker variety of the Omonville streaky gneiss only constitutes a small portion of the total rock exposed. The brown weathering variety, which is far more common, is different in several important respects from the darker variety. As may be seen from the modal analyses (table 4.3) it contains less plagioclase and more K-feldspar. Thus the occurrence of plagioclase phenocrysts is less common (see plate 4.7) and the proportion of finer grained groundmass

TABLE 4.3

MODAL ANALYSES OF OMONVILLE STREAKY GNEISSES

	*			Usual Variety				
	781	215	211	773	545	194	218	203
Quartz	25.2	19.3	19.2	24.4	23.5	21.7	24.0	18.5
Plagioclase	30.7	38.8	40.2	41.5	43.1	33.1	24.4	37.1
K-feldspar	35.4	30.1	23.2	21.9	21.1	32.6	38.2	29.7
Hornblende	6.7	2.8	0.3	4.8	-	4.8	3.5	-
Biotite	0.6	4.9	15.9	6.9	4.8	5.8	4.4	2.5
Chlorite	0.5	2.6	-	-	6.4	-	2.8	5.3
Ore	0.7	1.1	1.2	0.5	1.1	1.4	1.3	3.1
Epidote	-	0.2	-	-	-	0.7	1.3	3.7
Allanite	0.1	Trace	-	-	-	-	Trace	-
Q	27.6	21.9	23.2	27.8	26.8	24.8	27.7	21.7
P	33.6	44.0	48.7	47.2	49.1	37.9	28.2	43.5
A	38.8	34.1	28.1	24.9	24.1	37.3	44.1	34.8
$P/_{P+A}$	46.4	56.3	63.4	65.5	67.1	50.4	39.0	55.6
M	8.6	12.9	17.4	12.2	12.3	12.7	13.3	14.0
Counts	2000	2578	2044	2000	2084	3030	2211	1278

			Darker Variety		
	221	774	184	775	183
Quartz	22.0	23.0	17.0	20.9	9.5
Plagioclase	39.4	44.8	55.7	47.7	53.8
K-feldspar	18.3	18.4	9.9	13.7	0.8
Hornblende	6.6	6.0	9.7	11.0	27.4
Biotite	12.9	7.8	7.4	5.5	-
Chlorite	0.2	-	-	0.8	8.3
Ore	0.5	-	Trace	Trace	0.1
Epidote	-	-	-	-	-
Allanite	-	-	Trace	0.2	-
Q	27.6	26.7	20.6	25.4	14.8
P	49.4	51.9	67.4	58	83.9
A	23.0	21.3	12.0	16.6	1.2
$P/_{P+A}$	68.3	70.9	84.9	77.7	98.6
M	20.2	13.8	17.1	17.5	35.8
Counts	2130	2000	2321	2000	2000

* Plagioclase phenocryst poor variety.

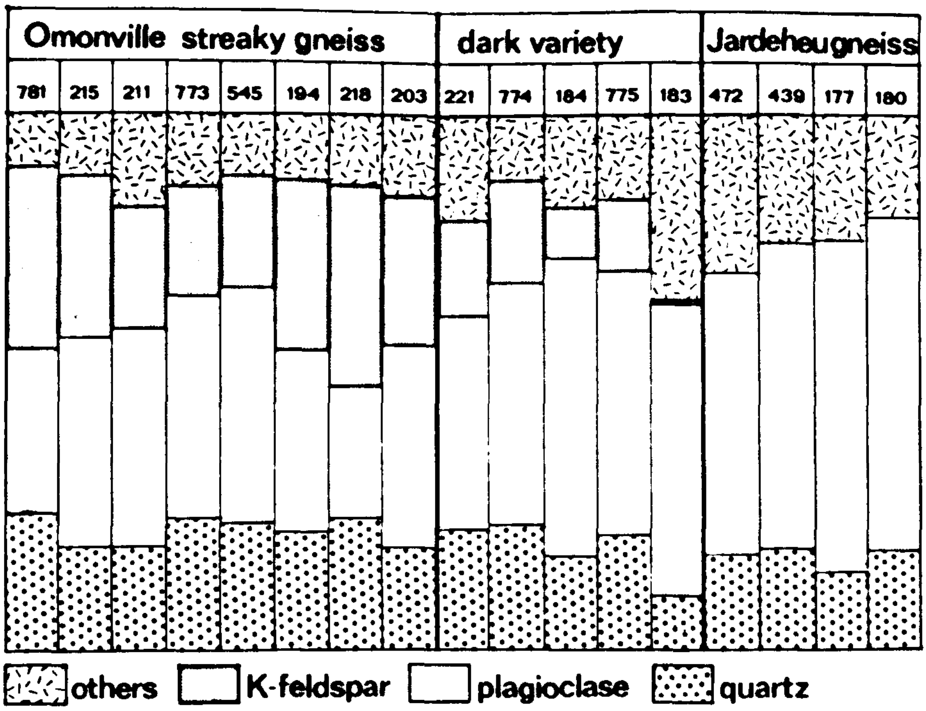
is much more dominant. Hornblende is not so abundant, particularly the larger grains with brown pleochroism. All the general features of the darker variety may be seen in the more usual variety. It is just the relative proportions of the constituents that have changed.

At the other end of the range of variation several specimens are found which only contain rare plagioclase phenocrysts and the finer grained groundmass has assumed overwhelming importance. These specimens are particularly characterised by the growth of areas of K-feldspar up to 2 mm in size either as single crystals or aggregates of several polygonal grains, (see plate 4.8). Perthitic textures are well developed and simple twinning with irregular, stepped composition planes are not uncommon. The margins of the K-feldspar appear cuspate and finger into the surrounding groundmass. The foliation in these rocks is accentuated by trains of opaque dust and fine grained (0.05 mm) biotite and blue green hornblende. Accessory minerals throughout the range of variation are apatite and brown euhedral zoned allanite.

A visual summary of the modal analyses of table 4.3 is given in figure 4.3A. In figure 4.3B they have been plotted in terms of plagioclase, quartz and K-feldspar and the modal analyses of the Jardeheu quartz dioritic gneiss are also plotted for comparison. Besides illustrating the tendency for the darker variety to have more plagioclase and less K-feldspar than the usual variety this plot also shows the more restricted range of composition of the usual variety. All the samples from the Omonville streaky gneiss plot on a fairly smooth trend of variation but it is noticeable that the samples from the Jardeheu quartz dioritic gneiss do not fall on this trend but slightly above it.

Structure of the Omonville Streaky Gneisses

The foliation developed in the Omonville streaky gneisses together with the associated lineation is undoubtedly a deformational fabric



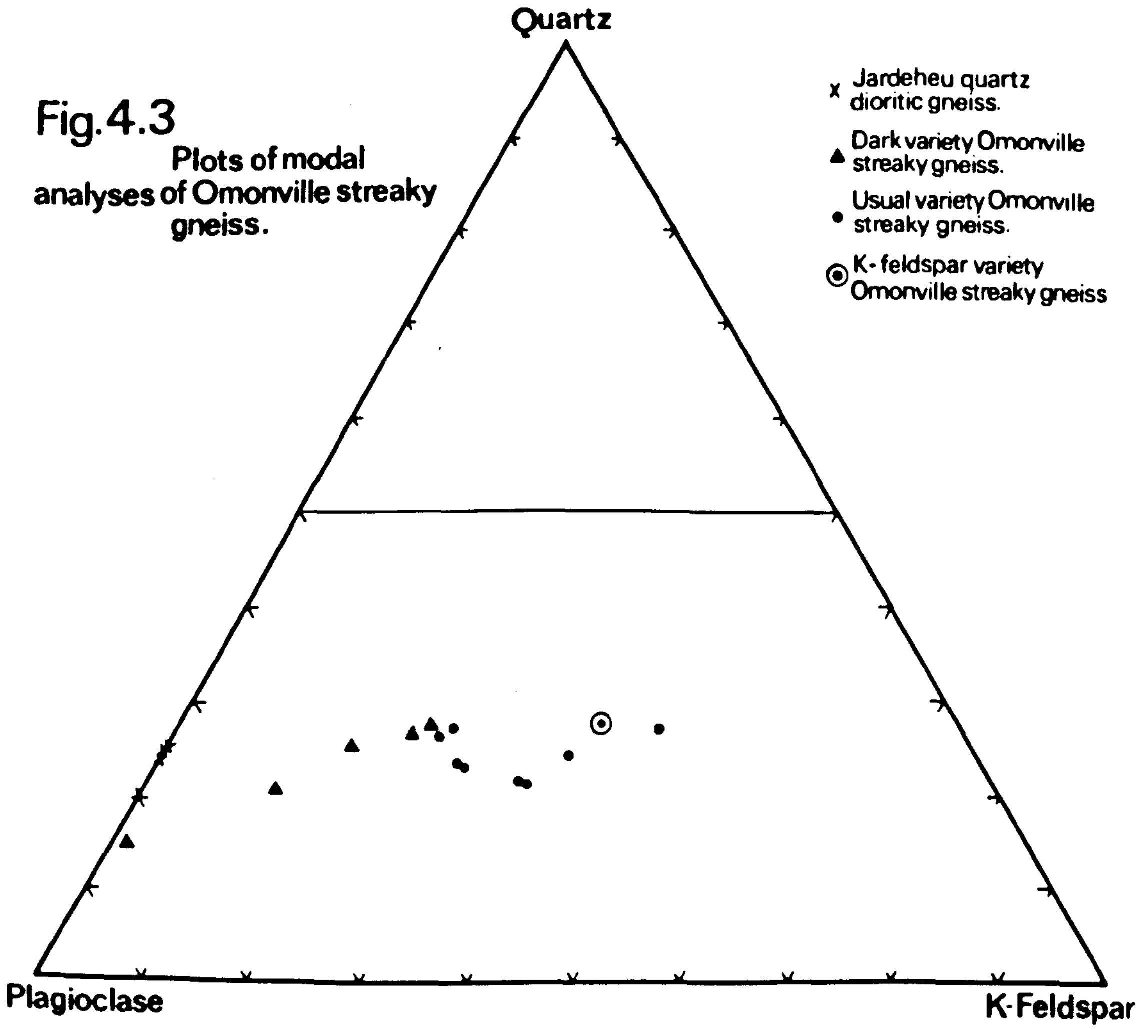


Fig.4.3
Plots of modal analyses of Omonville streaky gneiss.

which shows variations in the intensity of its development. This may be confirmed by the textures seen in thin section such as recrystallization, elongation of grains and the displacement of foliation around phenocrysts.

The lineation is formed by elongated patches of mafic minerals and when measured on the foliation surfaces it shows a reasonably consistent orientation at around 50°E of N and plunging 25°E (see figure 4.1B). The foliation shows a more complex distribution having what may be a systematic variation throughout the area. In the neighbourhood of Pointe Jardeheu it typically strikes 30°E of N and dips 40°SE, broadly parallel to the margins of the sheet-like bodies of the streaky gneiss. North of Port d'Omonville the gneiss is more massive in form and shows little trace of any foliation. Around le Fort at Omonville the streaky gneiss shows a foliation striking 60°E of N and dipping 60°N. Here, however, it is not possible to determine the form of the intrusive bodies and hence to establish any relationship between foliation and the attitude of the bodies.

Figure 4.1B shows the poles to the foliation and the lineations plotted on a stereographic projection. The distribution could be interpreted as showing the poles of the foliation forming a great circle and the lineations plotting close to the pole of that great circle. This could not result from a later folding of the foliation as there is no corresponding folding of the S_2 foliation. It would seem more likely that the foliation and lineation were formed by the same deformation, possibly close to the time of intrusion of the bodies. The attitude of the foliation may have been determined partly by pre-existing structures such as the S_2 foliation or the planes along which the sheet-like bodies were intruded and it may be partly fortuitous that the poles to the foliations appear to fall on a great circle.

As already described the foliation in the streaky gneisses post-dates the foliation in the Jardeheu quartz dioritic gneiss and as such it may be designated S_5. There is no indication of the possible time interval between the development of S_4 and S_5 and it could be that they were formed within a very short period of each other.

Chemistry of the Omonville Streaky Gneisses

A selection of specimens representing the whole range of mineralogical and textural variation found were chemically analysed for the major elements by X-ray spectrometry and the results are given in table 4.4.

The analyses are plotted on an AFM diagram in figure 4.4A. The specimens from the usual variety of the gneiss all plot close together, and it is only when those specimens from the darker variety and the plagioclase phenocryst poor variety are considered as well that an elongate trend is produced similar to a calc-alkaline trend. It should be emphasised that these two varieties only make up a very minor portion of the total exposed rock volume and that the usual variety occupies by far the largest volume. The Jardeheu quartz dioritic gneisses do not fall on this trend, and relative to them the dark variety of the Omonville streaky gneiss appears enriched in total iron content.

When the analyses are plotted on a triangular diagram for Na_2O, K_2O and CaO they form a smooth trend with increasing K_2O and decreasing CaO contents and the Jardeheu quartz dioritic gneisses plot at one extreme of this smooth trend. Again the usual variety alone shows very little variation.

Petrogenesis of the Omonville Streaky Gneisses

The chemical variation in the Omonville streaky gneisses is the result of variation in the relative proportion of plagioclase pheno-

TABLE 4.4

CHEMICAL ANALYSES OF OMONVILLE STREAKY GNEISSES

	*	*	*	Usual Variety					
	781	18	181	437	215	211	773	545	194
SiO_2	70.64	70.46	71.29	69.76	69.82	68.56	69.06	68.13	69.33
TiO_2	0.20	0.21	0.23	0.35	0.33	0.35	0.36	0.42	0.35
Al_2O_3	14.51	14.22	14.46	14.80	14.76	15.08	15.14	15.65	14.94
Fe_2O_3	1.47	1.82	0.90	0.83	1.79	2.17	1.68	1.81	2.13
FeO	1.18	2.07	2.05	2.91	1.91	2.45	2.31	2.72	2.04
MnO	0.04	0.05	0.05	0.05	0.05	0.07	0.06	0.05	0.06
MgO	0.37	0.37	0.39	0.80	0.73	0.77	0.72	2.16	0.81
CaO	1.51	1.56	1.50	1.89	2.34	2.08	2.40	0.80	2.35
Na_2O	4.01	4.31	4.40	4.45	4.15	4.36	4.15	3.91	3.84
K_2O	6.01	4.87	4.69	4.01	3.97	3.96	3.98	4.05	3.99
P_2O_5	0.06	0.06	0.06	0.14	0.15	0.15	0.14	0.29	0.15

* Plagioclase phenocryst poor variety.

	Usual Variety			Darker Variety				
	218	282	203	221	774	184	775	183
SiO_2	69.30	68.66	67.74	66.47	66.95	65.32	62.77	56.79
TiO_2	0.34	0.37	0.41	0.45	0.46	0.51	0.67	0.90
Al_2O_3	14.98	15.15	15.54	15.77	15.43	15.75	16.16	16.09
Fe_2O_3	2.19	2.20	2.91	2.23	2.05	2.31	2.59	2.87
FeO	1.93	2.17	2.15	3.06	3.38	3.52	4.61	6.13
MnO	0.06	0.07	0.10	0.08	0.08	0.10	0.10	0.15
MgO	0.76	0.85	1.07	1.02	0.92	1.18	1.63	5.09
CaO	2.53	2.39	1.99	2.94	3.14	3.44	4.11	6.57
Na_2O	4.03	4.01	4.27	4.29	4.24	4.29	3.95	3.19
K_2O	3.73	3.97	3.62	3.49	3.17	3.36	3.11	1.83
P_2O_5	0.15	0.16	0.19	0.21	0.20	0.23	0.31	0.38

Note: All analyses by X-ray spectrometry (FeO by titration) and recalculated to 100% on a water-free basis.

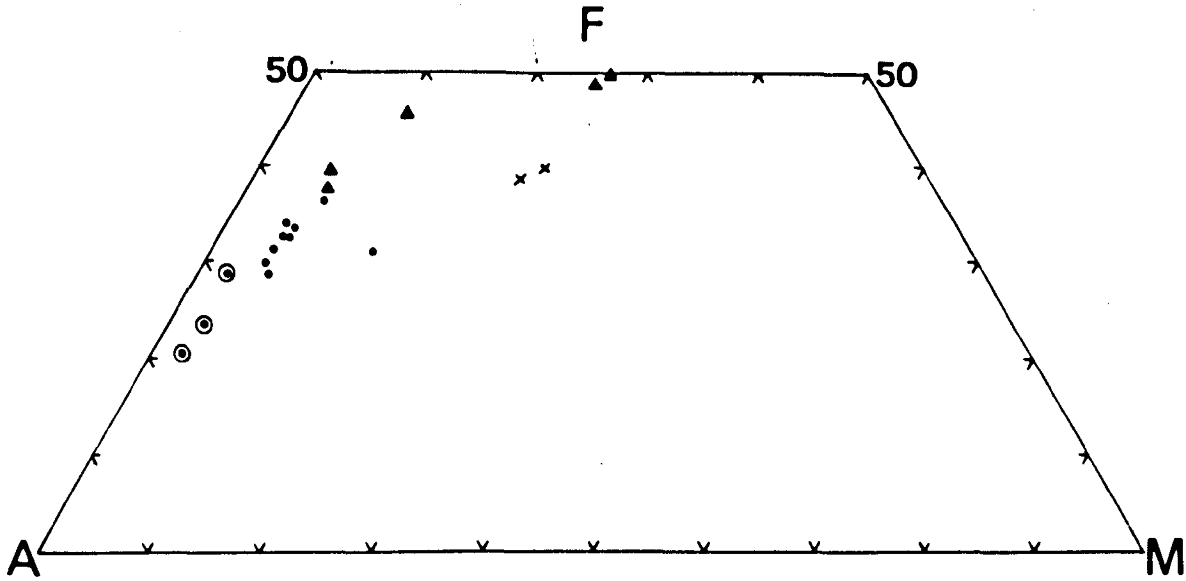
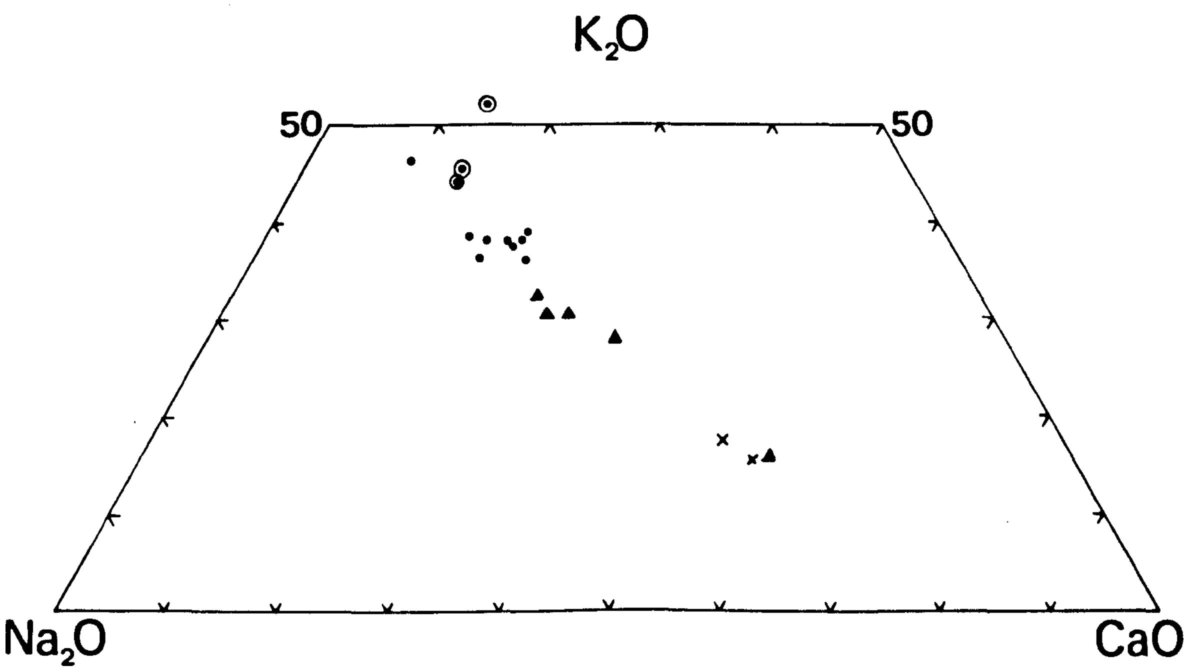


Fig. 4.4 Omonville streaky gneiss, AFM and Na_2O-K_2O-CaO plots.

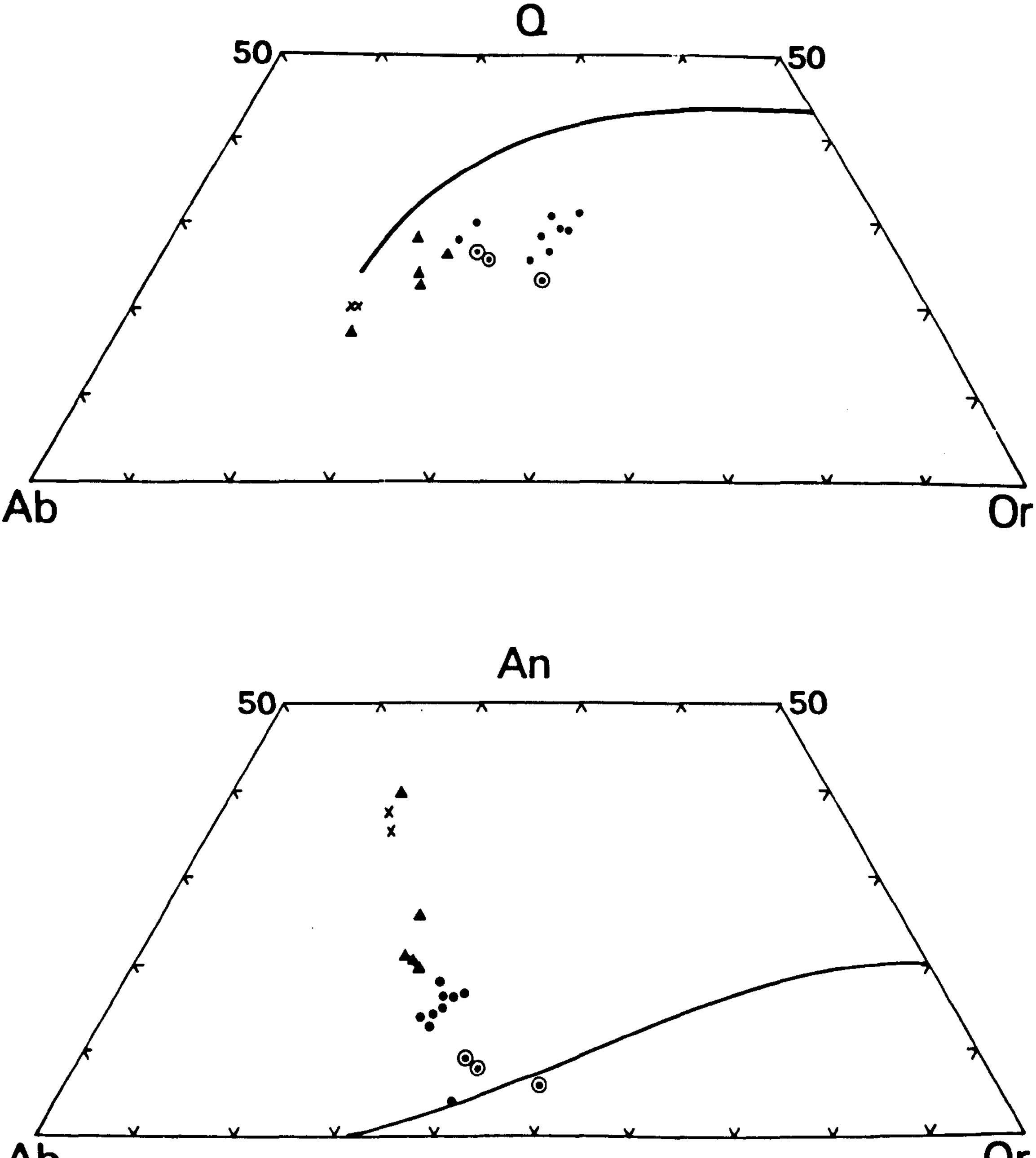


× Jardeheu quartz dioritic gneiss
▲ dark variety Omonville streaky gneiss
• usual variety ·· ·· ··
◎ K-feldspar variety ·· ·· ··

crysts and granitic groundmass present in the rock and marked variations only occur locally. This fractionation might result from local variations in the mechanics of intrusion of a viscous mass as a thin sheet. Alternatively, the concentration of phenocrysts could be, at least in part, contamination from the Jardeheu quartz dioritic gneiss. The dark variety has only been found in close association with the quartz dioritic gneiss as at Pointe Jardeheu and probably at Baie de la Rivière. It contains both mantled plagioclase phenocrysts, whose inner parts are similar in composition to those of the Jardeheu quartz dioritic gneiss, and partially replaced green-brown hornblende phenocrysts similar to the hornblende in the Jardeheu gneiss.

The larger part of the Omonville streaky gneisses is fairly uniform in chemical composition and plagioclase phenocrysts are uniformly distributed within it. The phenocrysts at some stage became unstable with respect to the granitic material now constituting the groundmass and they became mantled with albite. The phenocrysts could be xenocrysts representing the residua from an episode of partial melting which gave rise to the magma, or an early phase of crystallization from a liquid magma which was interrupted by a change in the conditions of crystallization.

Although the Omonville streaky gneisses cross-cut and have a foliation which is slightly oblique to the S_4 foliation in the Jardeheu quartz dioritic gneiss they could both be fairly closely related in time and origin. The chemical composition of the usual variety of the Omonville streaky gneiss would be consistent with it being a more evolved member of the same calc-alkaline series as the Jardeheu quartz dioritic gneiss. When the analyses are plotted on the Ab-An-Or and Ab-Q-Or faces of the system Ab-An-Or-Q (see figure 4.5) they could be interpreted as members of the same calc-alkaline series. Thus the Jardeheu quartz dioritic gneiss would represent the earlier cooled



Key as in figure 4.4

Figure 4.5. Omonville streaky gneiss, Ab-An-Or & Ab-Q-Or with projection of univariant line.

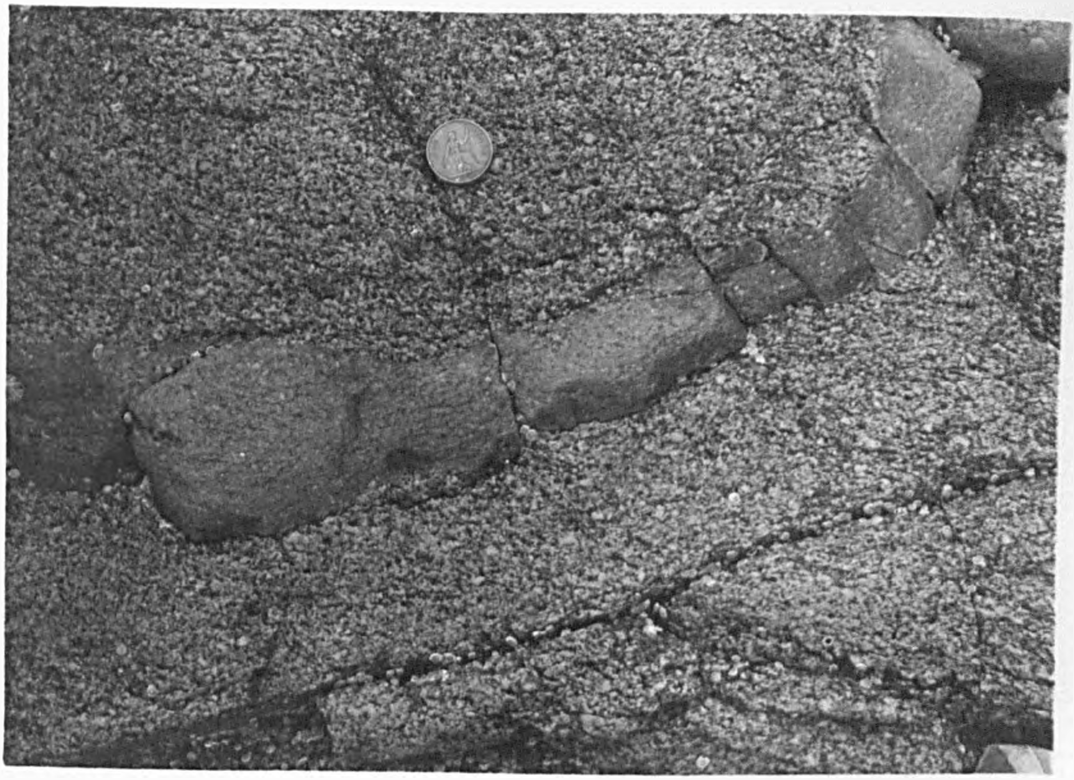
outer portion of a magma chamber and the usual variety of the Omonville streaky gneiss would represent a later more evolved granitic liquid containing plagioclase megacrysts of uncertain origin. This later fraction intruded into the roof and surrounding country rocks. Evidence for the presence of phenocrysts and granitic liquid has been preserved in the small bodies and thinner more rapidly cooled sheets. In the larger bodies reaction with the phenocrysts has been more complete and slower cooling has produced a more uniform slightly coarser grained rock.

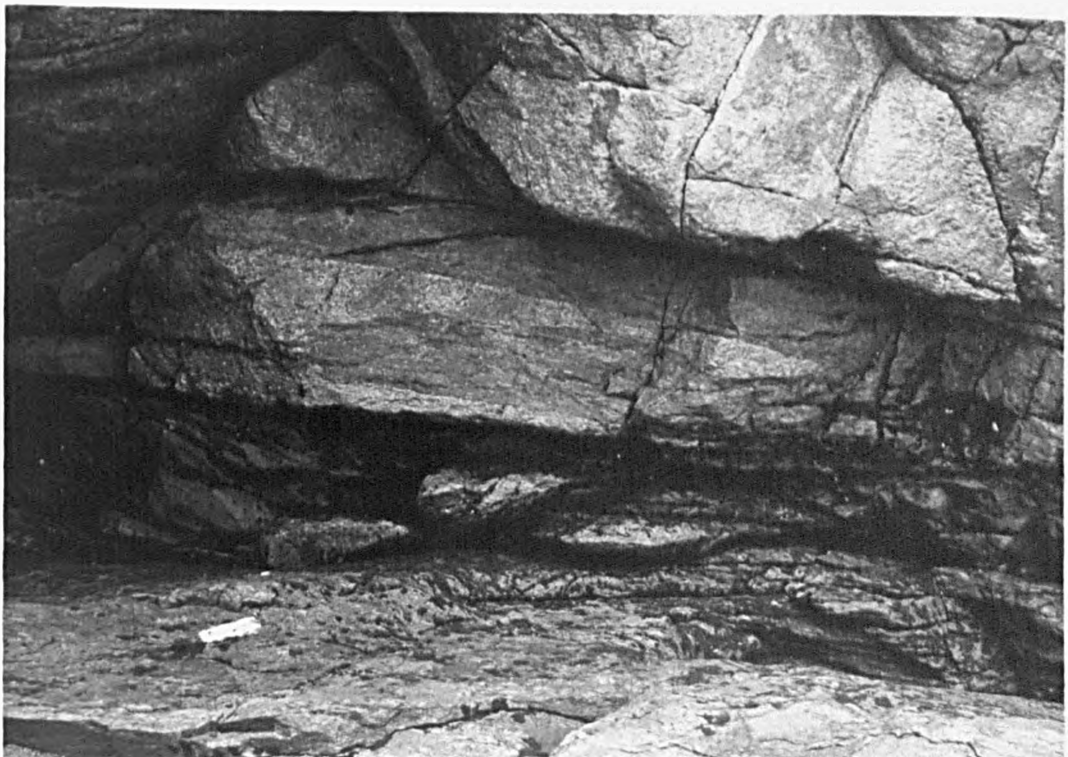
4.1 Banded amphibolite raft in gneisses, La Foireuse.

4.2 Composite gneisses cut by Omonville streaky gneiss (upper right), Baie de la Rivière.

4.3 Jardeheu quartz dioritic gneiss cut by vein of Omonville streaky gneiss, Pointe Jardeheu.

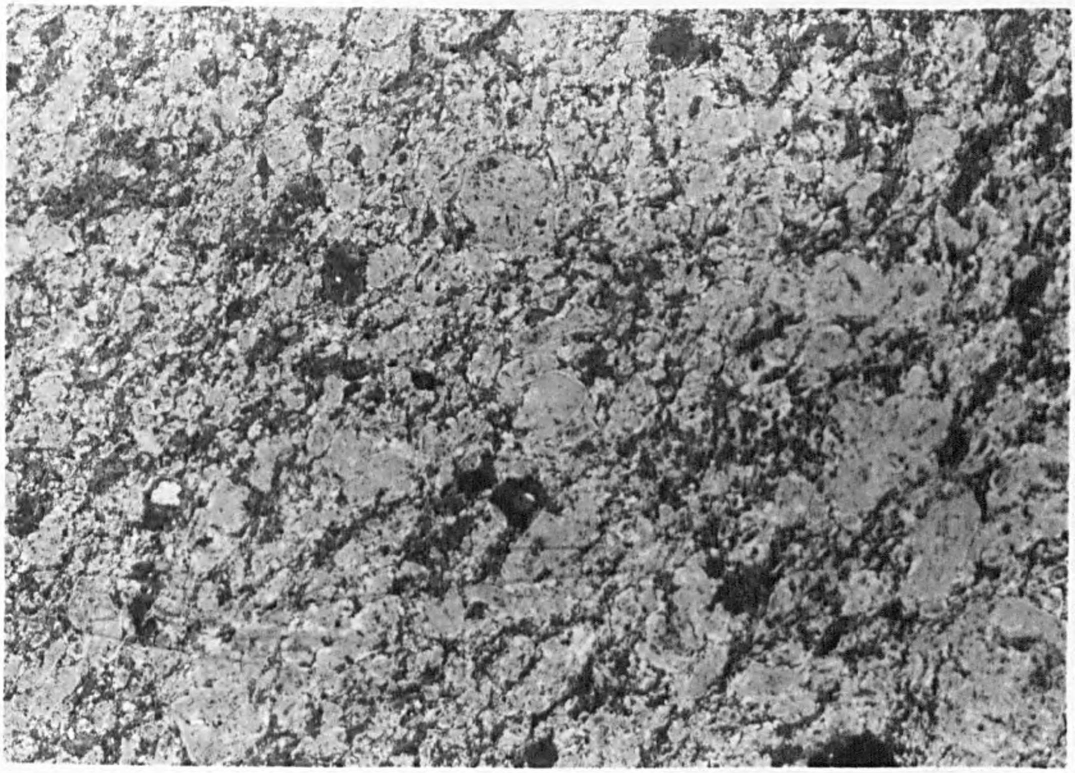
4.4 Interfingering (centre) of light and dark varieties of Omonville streaky gneiss, Pointe Jardeheu.





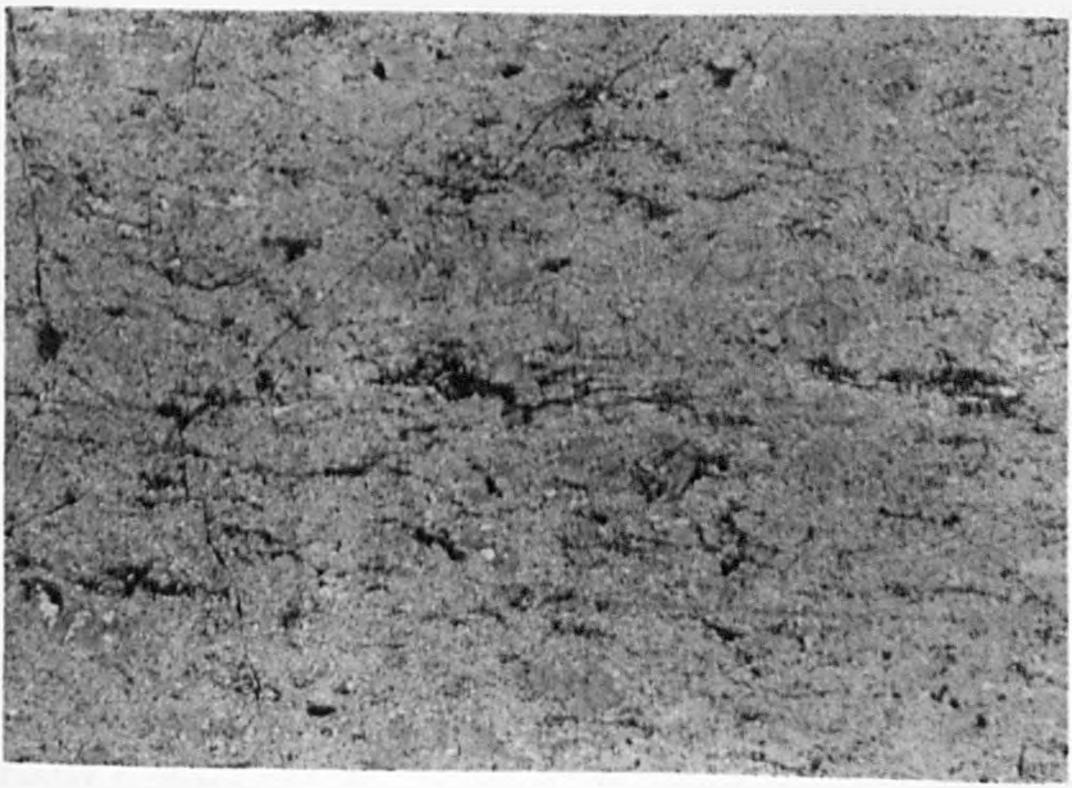
4.5 Dark variety of Omonville streaky gneiss with abundant mafic minerals. X8.

4.6 Dark variety of Omonville streaky gneiss with high proportion of zoned plagioclase phenocrysts. X8.



4.7 Usual variety of Omonville streaky gneiss showing plagioclase phenocrysts and fine grained granitic groundmass. X8.

4.8 Omonville streaky gneiss with K-feldspar phenocrysts and granitic groundmass. X8.



C H A P T E R 5

THE GNEISSES OF THE GRÉVILLE AREA

A third area of old rocks occupies the coastal strip from Baie de la Quervière to Landemer and as far inland as the overlying Cambrian sediments (see figure 2.1 and end maps 6 and 7). It is dominantly composed of K-feldspar augen gneisses but there are gradations into other varieties of gneiss. All the gneisses have suffered varying degrees of a strong cataclastic deformation which has often obscured any possible evidence of their earlier history.

At Landemer and also in the Baie de la Quervière a series of schists occur which have a structural history distinct from that of the gneisses. They have been assigned to the Brioverian but it has been admitted that there is no real evidence as to their stratigraphic level within the Brioverian (Graindor, 1960b). They are described in this chapter along with the gneisses in order that their structures may be compared.

The gneisses have many similarities with those of the other two areas already described particularly those of the Omonville area. In order to avoid undue repetition descriptions of the banded gneisses and inclusions of metabasic and metasedimentary rocks will not be repeated here. An outline of the sequence of events for the gneisses of the Gréville area is given in table 5.1.

The K-feldspar Augen Gneiss

The K-feldspar augen gneiss is found along the coast from Le Hablet to Havre du Vuoy. It has all the appearances of having been produced by the ductile deformation of a pre-existing granitic rock

TABLE 5.1

SEQUENCE OF EVENTS IN THE GNEISSES OF THE GRÉVILLE AREA

Event	Evidence
Sedimentation	Sediments now banded gneisses.
Basic lavas or dykes	Metabasic lenses in gneisses.
Intrusion of K-feldspar granite	Now K-feldspar augen gneiss.
D_1 deformation and production of S_1 banding	Early banding seen in gneisses.
Metamorphism, M_1	Gneissose banding suggests amphibolite facies.
D_2 deformation of gneiss and production of main foliation S_2	Main foliation in gneisses.
Metamorphism, M_2	Amphibolite facies assemblages in gneisses.
Intrusion of basic dykes ?	Now deformed dykes which cross-cut S_2 but are foliated.
D_3 deformation	Small scale kinks in S_2
Intrusion of basic dykes	Now deformed dykes which cross-cut S_2 but are foliated.
Strong cataclastic deformation and production of S_H foliation.	Shear foliation S_H in gneisses cross-cuts S_2,
Metamorphism, M_{2S} ?	Greenschists facies minerals, chlorite, calcite, etc.

TABLE 5.1
(Continued)

SEQUENCE OF EVENTS IN THE GNEISSES OF THE GRÉVILLE AREA

Event	Evidence
Intrusion of Sabine diorite and deformation producing foliation in diorite.	Sabine dioritic gneiss cross-cuts S_H in gneisses and is foliated.
Intrusion of small, foliated acid bodies.	Cross-cut S_H in gneisses. Relationship to Sabine dioritic gneiss not known.
Flow banded felsite bodies	Cross-cut S_H in gneisses.

during the D_1 and D_2 deformations. It is very variable in character. The K-feldspar augen vary in size from 0.5 to 5 cm with an average size of about 2 cm. The proportion of K-feldspar augen in the rock is also variable and sometimes only sporadic K-feldspars are seen. In some places the K-feldspars have a classic augen shape and the plagioclase and quartz bands are displaced around them. Elsewhere, the K-feldspar is much more part of the foliation and it appears as almost continuous bands within the foliation. This difference could be the result of heterogeneous deformation producing the main foliation (S_2) in the gneiss. There is abundant evidence suggesting that most of the K-feldspar does not post-date the D_2 deformation. The augen shape of the grains and the occurrence of pegmatitic patches of K-feldspar with the foliation displaced around them supports this contention. Some K-feldspar veins exhibit ptygmatic folds. However, some of the K-feldspar is later as large K-feldspar crystals are found filling tension gashes and some foliated K-feldspar veins cross-cut the S_2 foliation in the gneiss.

The K-feldspar augen gneiss is composed of quartz, plagioclase and K-feldspar together with chlorite. The plagioclase is oligoclase (An_{12}) in composition and often rather altered. It forms bands 2 mm wide of grains up to 1 mm in size which are slightly elongated or ovoid parallel to the banding. Quartz forms discontinuous bands up to 2 mm wide and elongate patches. Individual grains of quartz range in size from 0.1-0.3 mm and often have complex crenulate margins although some areas of polygonal grains do occur.

K-feldspar varies considerably in grain size and may form isolated grains within the quartz bands as well as larger augen. It is microcline perthite and cross-hatch twinning is often well developed. Myrmekite is frequently formed at grain boundaries and the grains often contain partly adsorbed plagioclase. Micro-fractures and shadowy extinction are not uncommon and there is no evidence that the K-feldspar post-dates the D_2 deformation.

Chlorite, α: yellow, β, γ: green, occurs as straggly flakes often choked with opaque inclusions both along grain boundaries and in bands parallel to the foliation.

In thin section it is also possible to recognise the progressive development of a cataclastic texture. For a typical quartz + plagioclase + K-feldspar rock the original texture is modified by the development of clasts around 5 mm in size with rather angular margins. They tend to be composed of more than one mineral and consist of a number of grains. Individual grain boundaries are complex and may show recrystallization textures. Quartz shows undulose extinction. K-feldspar has well developed cross-hatch twinning and patchy extinction, while plagioclase shows deformation twinning and kinked twin lamellae. Small displacements along microfractures in the feldspars are common. The groundmass between the clasts as well as finely granulated quartz and feldspar contains small flakes of sericite and chlorite but the relative proportion of clasts to groundmass is large.

Even within a single thin section modification of this early cataclastic texture may be observed. The clasts become smaller and more rounded and there is an increase in the amount of recrystallization at grain boundaries within the clasts. The proportion of inter-clast material increases and the zones between the clasts may reach 2 mm wide. Muscovite flakes (0.1 mm in size) are sporadically developed in the fine grained sericite groundmass.

Specimens from well developed shear zones are fine grained and have a prominent new foliation which is wavy in nature. This is because it has been displaced around augen shaped clasts of altered plagioclase and quartz 0.2-0.3 mm in size. The relative proportion of clasts is now less than 50% of the rock. The foliation is defined by streaks of fine grained opaque minerals and flakes of sericite and chlorite in the groundmass.

The minerals formed at the time of the shearing included sericite, muscovite and chlorite and in one or two instances biotite was recorded as well. Some of the cataclased gneisses also contain rare calcite and epidote. The calcite appears to post-date the cataclasis and occurs as small (0.1 mm) polygonal grains in little clusters in cracks and between clasts. Thus it would appear that the deformation took place under low grade metamorphic conditions. The textures described, such as microfractures, narrow zones of shear displacement cutting several grains and angular and multigrain fragments all suggest brittle deformation rather than ductile deformation combined with recovery and recrystallization of phases (Bell and Etheridge, 1973).

Deformed Basic Dykes

The deformed basic dykes of the Gréville area are rather less informative than those of the Nez de Jobourg area. All those examined cross-cut the main foliation (S_2) in the gneisses. One deformed dyke has been cut by a sheet of foliated acid material which also showed a later cataclastic deformation. This suggests that at least some of the dykes pre-date the shearing in the gneisses. The dykes all show the metamorphic mineral assemblage, albite + chlorite + epidote + sericite ± actinolite + magnetite. Thus they may be described as post-D_2 dykes which have suffered a fairly complete retrogressive metamorphism. The time of this metamorphism cannot be specified exactly but may well have coincided with the shearing of the gneisses.

Several large basic dykes up to 20 or 30 m wide were found to have sheared margins. In thin section, however, they showed a good igneous texture with a superimposed cataclastic texture rather than a completely metamorphic foliation. These dykes are most probably post-Cambrian in age.

Structure of the Gneisses

The early structural history of the gneisses is essentially similar to that of the gneisses of the other two areas. As summarised in table 5.1, it is envisaged that following the deposition of a series of sediments, now represented by the banded gneisses, a granite was emplaced and all were deformed producing the early banding S_1. The main foliation (S_2) was produced during the second deformation. Figure 5.1A is a plot of S_2 and L_2. There is a spread in the trend of S_2 from north to east although the main concentration trends 60-70°E and dips at a moderately steep angle to the south-east. The lineations plunge at a shallow angle to the south-west. The spread in the orientation of S_2 and L_2 is probably the result of a later deformation although this cannot be convincingly demonstrated on the ground.

The S_2 foliation has been folded on a small scale by a series of kinks exactly similar to those described in the Omonville area and seldom exceeding 20 cm in size. They usually plunge at an angle somewhere between 50° and 80° towards ESE and have steep axial planes trending ESE. This is a swing in trend of about 45° towards the south compared with those of the Omonville area. It is considered that these small folds were formed prior to the shearing of the gneisses as the shear foliation was never found to have been deformed by them.

Perhaps the most striking feature of the gneisses is the cataclastic deformation they have suffered. This is in marked contrast to the gneisses of the other two areas which generally show little evidence of this type of deformation. The intensity of the development

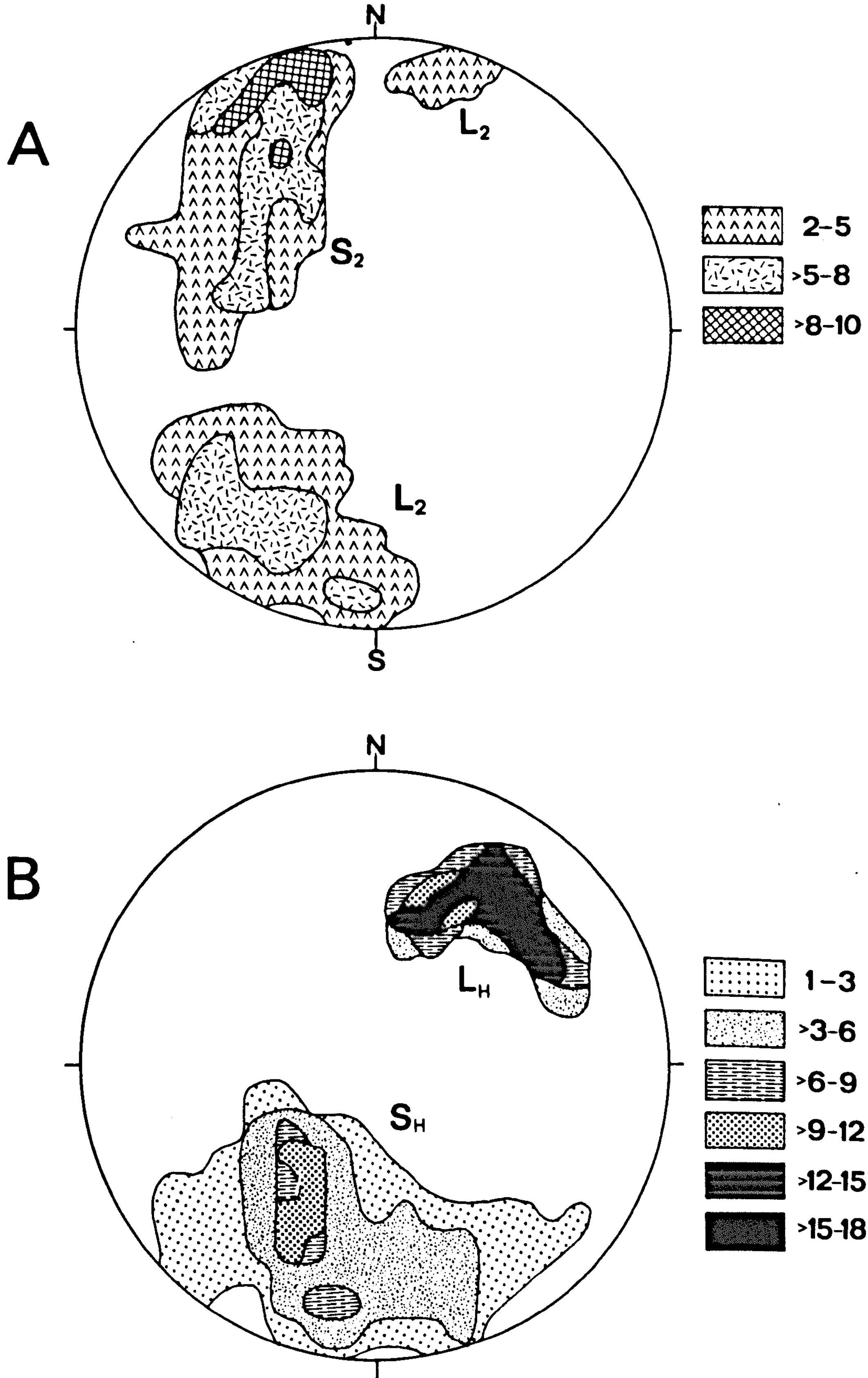


Fig.5.1. Gneisses of the Gréville area.

A. 100 poles to S_2 foliation, 130 L_2 lineation.

B. 200 poles to S_H foliation 70 L lineation.

of this deformation is very variable. It is particularly intense to the east of the Baie de la Quervière and also just to the west of Landemer. That is, in both cases, close to the contact between the gneisses and schists.

Approaching the contact at Landemer the gneisses show a progressive increase in the apparent degree of deformation they have suffered. 400 m along the coast from the contact the S_2 foliation in the gneisses is readily recognisable and shearing is confined to long, narrow zones about 1 m wide and trending between 120 and 140°E of N. At a distance of 300 m a cataclastic texture in the gneiss becomes obvious and the shear zones increase in number and width. At about 150 m the more obvious foliation is the shear foliation and it is difficult to pick out the S_2 foliation. The cataclased gneiss looks greener in colour and masses of gneiss are completely isolated and surrounded by zones of intense shearing. Closer to the contact the gneiss becomes flaggy in character as a result of the strong shear foliation (see plate 5.2).

Throughout the whole coastal section between Quervière and Landemer similar variations in the intensity of the shear foliation occur. Thus some areas of gneiss are virtually unaffected by shearing except perhaps for the occasional thin shear zone while others show a very prominently developed shear foliation. The poles to the shear foliation (S_H) are plotted on the stereogram of figure 5.1B. They show a spread of values but a concentration occurs with trends around 120°E of N dipping at a moderate angle to the north-east. The variation in attitude of the shear foliation may be no more than is characteristic of this type of deformation rather than the result of a later deformation. A strong lineation (L_H) on the shear foliation surface is caused by the intersection of the S_1 banding and S_2 foliation with the S_H surface. Figure 5.1B shows that the lineations plunge north-east at an angle of about 30°. The spread of values is probably the combination of the variation in the attitude of S_2 when S_H was formed together with the variation in S_H.

The Sabine Dioritic Gneiss

The Sabine dioritic gneiss forms the headland on the west side of Baie de la Querviѐre. On each side of the headland a small strip of sheared gneisses separate it from, on the one hand, Cambrian sediments and on the other the mica schists. In the west corner of Baie de la Querviѐre veins of dioritic gneiss cross-cut the shear foliation in the sheared gneiss suggesting that the dioritic gneiss was emplaced after the formation of the shear foliation. This view is supported by the fact that the dioritic gneiss does not have a strong shear foliation developed in it. The dioritic gneiss and the schists were not found in contact at any point and it is not possible to establish the age relations between them. The schists close to the dioritic gneiss show no signs of contact metamorphism. The dioritic gneiss has undergone some cataclastic deformation and this is more apparent towards the eastern side of the outcrop. It has also been cut by basic dykes which show an igneous texture modified by this cataclastic deformation. It is suggested that this deformation may be post-Cambrian in age.

Dioritic rocks are found inland in several poorly exposed localities and these are probably of a similar origin to the Sabine dioritic gneiss. The limits of their outcrop is tentatively given on end map 1 but this is a very conjectural boundary.

The dioritic gneiss is medium grained and is characterised by the granular appearance of the light coloured plagioclase crystals which are often partly surrounded by chlorite and hornblende. Both the plagioclase and the mafic patches tend to be dimensionally orientated giving rise to a distinct foliation. The foliation is almost vertical and strikes north-east, which is nearly at right angles to the shear foliation in the gneisses.

In thin section the dioritic gneiss is seen to be dominantly composed of plagioclase with minor ragged hornblende and abundant chlorite. Sphene is a common accessory mineral.

Plagioclase is andesine (An_{32}-An_{36}) in composition. It occurs as ellipsoidal grains 1-3 mm in size and is often rather altered. The central parts of the grains may be cloudy with fine grained opaque minerals and alteration products. Chlorite is developed along grain boundaries. Some specimens show albite (An_9) forming small patches between the larger grains and as veins running along fractures. Quartz is variable in amount but is not abundant. It forms interstitial patches 1-2 mm in size of strained grains and also stringers which may show polygonal recrystallization.

Hornblende, α : light brown, β : green, γ : dark green is only a relatively minor constituent. It forms ragged, rather 'dirty' subhedral grains about 1 mm in size with irregular margins. They often contain inclusions of quartz, opaque dust and occasionally sphene and may be extensively altered to chlorite. Chlorite is relatively abundant both along grain boundaries and in patches 1-2 mm in size composed of an interlocking network of small flakes intergrown with epidote, apatite and opaque minerals.

Foliated Acid Bodies

Small acid bodies, dyke-like in form, cross-cut the shear foliation (S_H) in the gneisses. They are not common. They are medium to fine grained, grey in colour and may show small weathered out phenocrysts. They have a faint foliation. In thin section they may be seen to contain plagioclase phenocrysts and fine grained quartz, plagioclase and chlorite. The fine grained plagioclase forms grains which show radiating crystallites. It is considered that these are probably younger than the Sabine dioritic gneiss but no firm evidence was found.

The Schists at Landemer and Baie de la Querviè re

At Landemer and also at Baie de la Querviè re a series of mica schists are found. They are black in colour and have a prominent foliation dipping at a low angle towards the north-east. They erode easily and now form a low lying tidal platform and, as a result, it is not easy to reconstruct their geological history. The sequence of events summarised in table 5.2 is that which has been established from the available evidence.

Interlayered with the dark schists are thin bands up to a few centimetres thick of a lighter colour, sometimes weathering light orange. These bands may be used to demonstrate that the schists have been folded in a series of small scale recumbent isoclinal folds (see plate 5.5) with their axial planes parallel to the main foliation (S_{2S}) in the schists. The main foliation has been deformed by two types of later minor folds (see plate 5.6) but these are only developed to a limited extent.

In thin section the schists may be seen to be composed of quartz + muscovite + graphite + pyrite $\pm$ calcite. The earliest structures take the form of thin bands of quartz with muscovite flakes developed parallel to them. This is an early metamorphic foliation (S_{1S}).

In specimens where the recumbent folds have been preserved, thin sections cut across the folds show that the S_{1S} foliation has been deformed (see figure 5.3A). On the limbs the quartz bands are boundinaged with considerable recrystallization at the points of rupture, and on the crests the quartz bands are completely recrystallized with the new grains elongated parallel to the axial

TABLE 5.2

SEQUENCE OF EVENTS IN THE MICA SCHISTS OF LANDEMER AND BAIE DE LA QUERVIÈRE

Event	Evidence
Deposition of sediments	Now deformed metasediments at Landemer and Baie de la Quervière.
D_{1S} deformation and production of foliation S_{1S}	Quartz banding and mica foliation in schists.
Metamorphism, M_{1S}	Green schist facies assemblages.
D_{2S} deformation and production of recumbent folds and S_{2S} foliation.	Recumbent isoclinal folds deform S_{1S}. Main foliation S_{2S} is axial planar to recumbent folds and has lineation L_{2S} parallel to fold axes.
Metamorphism, M_{2S}.	Recrystallization of quartz, musovite, chlorite.

Note: The shear foliation S_H in the gneisses seems likely to have been produced at the same time as S_{2S} foliation.

- S_H, the contact between gneiss and schists and S_{2S} are all parallel.
- L_H is parallel to L_{2S}.
- The shear foliation S_H increases in intensity towards the contact between the gneiss and schists.
- S_H is not developed in the areas of gneisses which do not have contacts with schists (Omonville, Nez de Jobourg).
- Both S_H and S_{2S} formed under low grade metamorphic conditions.

Event	Evidence
Formation of kinks and open folds.	Two minor fold types are seen folding S_{2S}. No evidence of relative time.

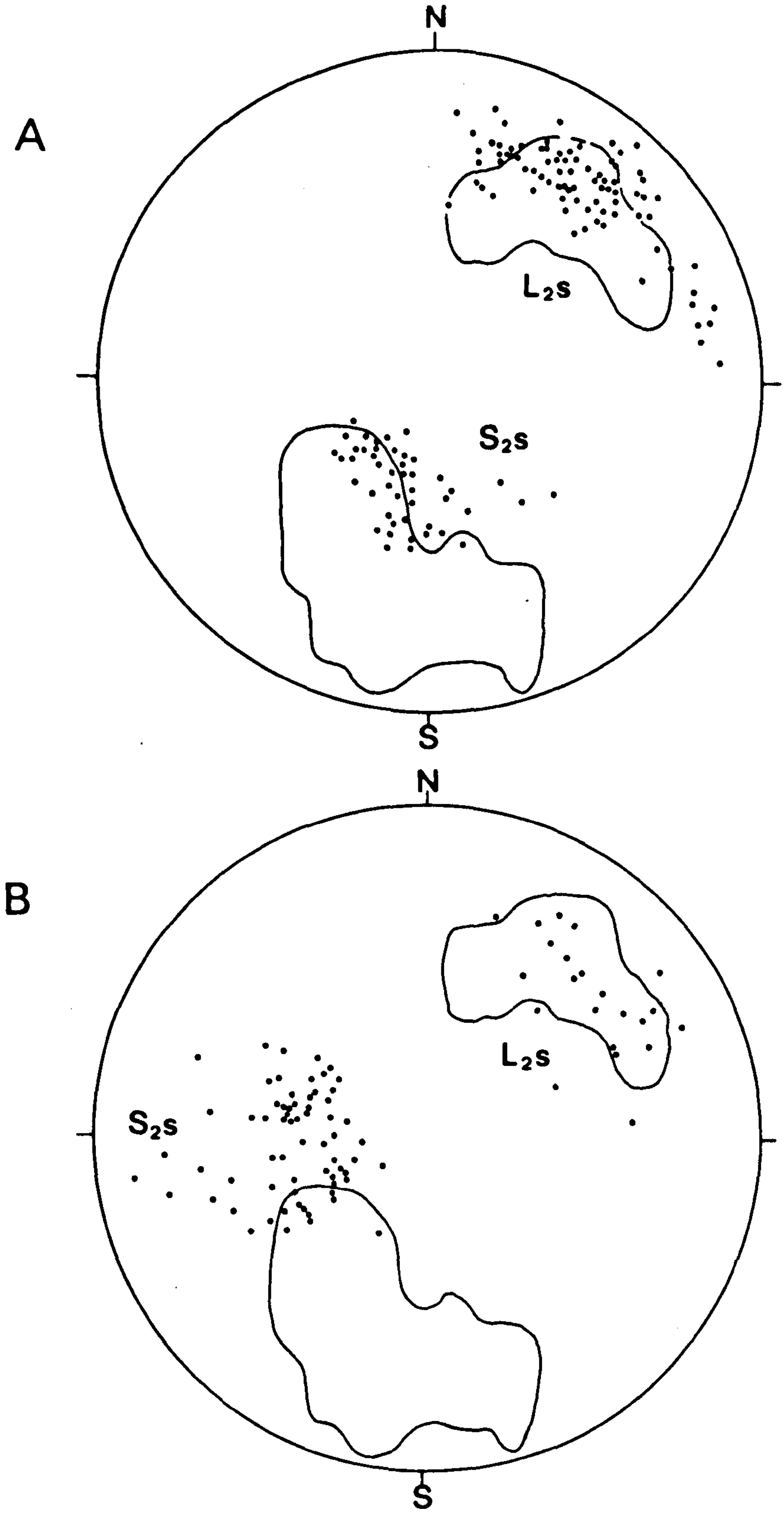


Fig. 5.2. Mica schists:

A Landemer

B Baie de la Quervière

Showing poles to S_{2s} foliation and L_{2s} lineations. Outlines S_H and L_H see Fig. 5.1.

planes of the folds. However, apart from this, a new axial plane foliation is not obviously developed in the fold hinges. Elongate muscovite flakes may be seen to have been folded around the nose of the folds and clearly pre-date this deformation.

Other specimens without well preserved recumbent folds may be interpreted as showing a S_{2S} foliation (see figure 5.3B). These have a strongly developed foliation mainly defined by muscovite flakes cloudy with fine grained opaque inclusions. Enclosed by this foliation are lenticular areas which have a foliation oblique to the prominent foliation. It is formed by muscovite flakes, by boudinaged quartz bands and by trails of euhedral pyrite crystals with quartz 'pressure shadows'. This is interpreted as relict S_{1S} foliation which has suffered deformation sufficient to obliterate any recumbent fold hinges but not sufficient to completely transpose it parallel to the new S_{2S} foliation. Other specimens with a single dominant foliation show relict S_{1S} quartz banding as isolated stringers with the quartz completely recrystallized to a very fine grained mass. The possibility that in both these examples the prominent foliation is later than the deformation producing the recumbent folds cannot be ruled out but is considered unlikely as the main foliation observed in the field is always axial planar to the recumbent folds.

At Landemer the main foliation in the schists strikes approximately 110°E of N and dips at about 25°NE (see figure 5.2A). A prominent lineation (L_{2S}) is developed on this surface and is formed by the intersection of the folded colour banding. The trend of this lineation varies from north to east although there is a concentration of points at about 40°E of N plunging at 25°NE (see figure 5.2A). The recumbent folds have axial planes parallel to the S_{2S} foliation and fold axes parallel to the L_{2S} lineation. The S_{2S} foliation has been folded into a series of small scale kinks which have fold axes plunging 30° towards around 30°W of N and axial planes with a similar trend dipping 80°E. Small scale gentle open folds of the S_{2S} foliation have almost vertical axial planes trending 30°E of N and fold axes plunging 20° towards 30°E of N.

At Baie de la Querviѐre the outcrop of the schists is only about 200 m wide and measurements taken here may reflect rather local variations in trend. The S_{2S} foliation strikes somewhere in the region between 30° either side of N and dips at about 30°E (see figure 5.2B). This is a difference of about 90° in strike compared with the direction at Landemer. The L_{2S} lineation, however, has a similar orientation to that at Landemer plunging at about 30°NE (see figure 5.2B). The kinks have fold axes plunging at 25° towards 70°E of N and steep axial planes trending in a similar direction which is a difference of about 90° from their orientation at Landemer.

Relationship Between the Gneisses and Schists

As previously stated the schists at Landemer were assigned to the Brioverian by Graindor (see Graindor, 1960b). This correlation was made on the basis of the lithology and structural style of the schists and on the low metamorphic grade of the schists compared with that of the nearby gneisses. In the absence of any evidence to the contrary the schists are accepted as younger than the gneisses for the following discussion.

End map 7 shows that at Landemer the S_2 foliation in the gneiss is steeply dipping and strikes at a high angle to the contact with the overlying schists. This demonstrates that the contact post-dates the formation of the S_2 foliation in the gneiss. The shear foliation (S_H) in the gneiss increases in intensity as the contact is approached. This foliation is approximately parallel to the contact and parallel to the main foliation (S_{2S}) in the schists. Both foliations were formed under similar low grade metamorphic conditions. The lineations L_H in the gneiss and L_{2S} in the schists are parallel.

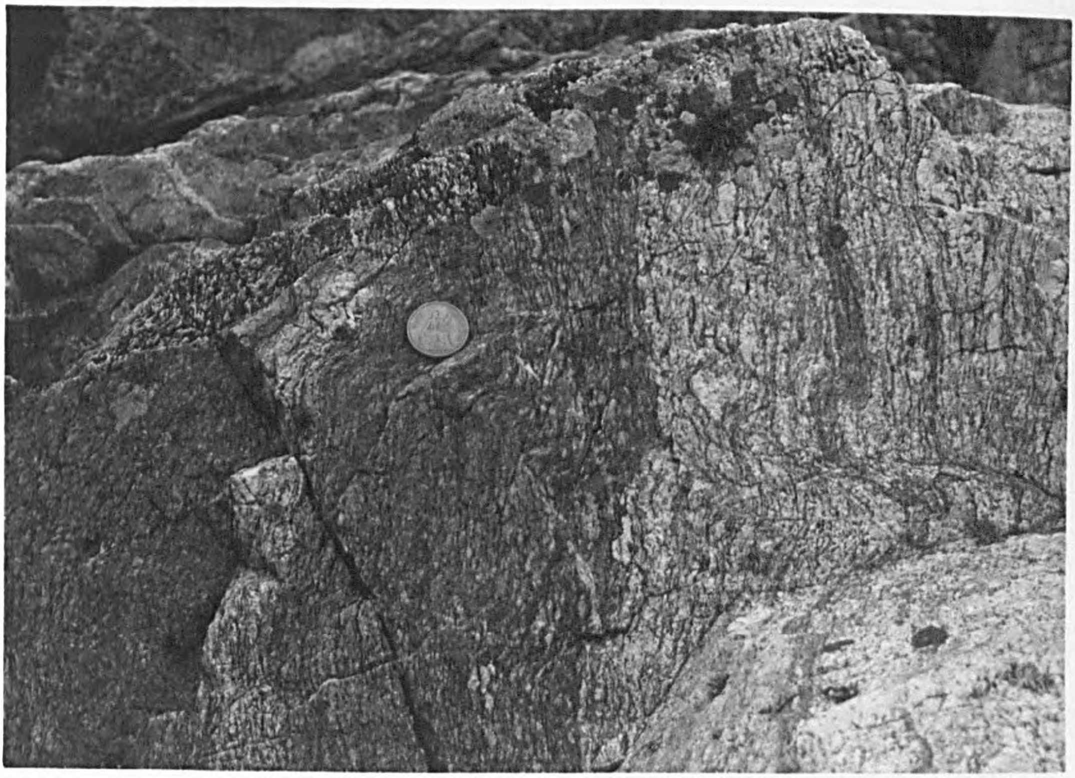
In the light of the above information it is possible to discuss the relative age of the shear foliation (S_H) in the gneisses. If the shear foliation were of Pentevrian age the parallelism of structures described would seem to be a coincidence, but it would be an even more remarkable coincidence that the intensity of the deformation should be directly related to the position of the contact and that this foliation should only be developed within the one area of gneisses that contained the schists. Accordingly, it is considered more likely that the shear foliation is of post-Pentevrian age. If the S_H foliation was formed at the same time as the S_{1S} foliation in the schists then it would seem surprising that it would appear to have been unaffected by the later deformation producing the S_{2S} foliation. The most reasonable explanation is that the S_H foliation in the gneisses was formed mainly at the same time as the S_{2S} foliation in the schists. Explanations involving post-Cambrian thrusting would appear to be unsatisfactory when the orientations of structures in the Cambrian sediments (see Chapter 7) are compared with the orientation of S_H and S_{2S}.

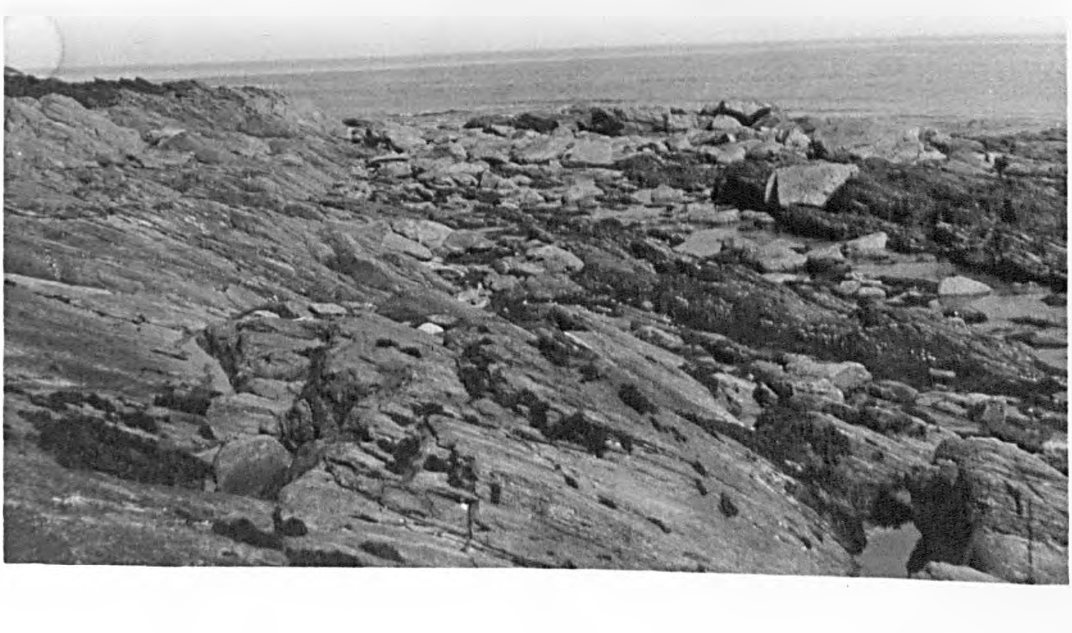
The intense shearing of the gneisses associated with the contact at Landemer makes it seem unlikely that an original sedimentary relationship between the schists and the gneiss has been preserved. It may be significant that neither at Landemer nor at Baie de la Querviѐre is there any sign of any sort of basal conglomerate at the contact.

At Baie de la Querviѐre there is little doubt that the contacts between gneiss and schists are tectonic. On the east side of the bay very sheared gneiss overlies schist. The schists show some lithological variation with those at the back of the bay being grey-green in colour, coarser grained than the black schist and containing a high proportion of calcite. They could represent an original calcareous mud. The boundary between these lithological variations, although folded now, strikes directly under the sheared gneiss contact as does the S_{2S} foliation in the schists (see end map 6). This suggests that the sheared gneiss was emplaced in its present position not earlier than a late stage in the D_{2S} deformation. It is possible that some of the thrusting is post-Cambrian in age and related to the thrusting in the nearby Cambrian sediments (see Chapter 7). That is, the contact between schists and sheared gneisses may have been modified to its present form by post-Cambrian thrusting.

5.1 Banded gneiss with K-feldspar augen, Havre de Vouy.

5.2 Contact between sheared gneisses of the Gréville area and (right) schists, Landemer.





5.3 Shear zone in gneisses, le doue du moulin.

5.4 Zone of intense dislocation in gneisses, le doue du moulin.

5.5 Recumbent F_{2S} folds in schists,
Baie de la Querviere.

5.6 Late kinks in schists, Landemer.

CHAPTER 6

THE NORTHERN GRANITIC ROCKS

Introduction

The entire north-west corner of La Hague from west of Pointe Jardeheu to south of La Roche and inland almost as far as a line drawn between the churches at Jobourg and Digulleville is occupied by granitic rocks (see figure 2.1). In the first section of this chapter the distinctive granitic rock with K-feldspar megacrysts and green finer grained inclusions, which may be seen in the Anse St. Martin, is described. It is probably older than all the other granitic rocks of this area. It was described by Jérémine (1924) as "le granite à enclaves de la Hague" and is referred to here as the St. Martin monzonite.

The other granitic rocks of this area have previously been referred to as the Auderville granite (see for example, Jérémine, 1930; Graindor, 1960b), although the granite on the headland west of Pointe Jardeheu has usually been treated separately ("le granite alcalin de l'anse St. Martin" of Graindor, 1960b). Jérémine (1930) pointed out that there are compositional differences within the Auderville granite but did not elaborate on them. Detailed field mapping shows that there are not only compositional and textural differences within the rocks previously described as the Auderville granite but also that a sequence of intrusive events may be established (see table 6.1). This sequence may include "le granite alcalin de l'anse St. Martin" (called here the Ecuty granite). To avoid confusion the name Auderville granite is not used. Each intrusive phase has been given a separate name and they are referred to collectively as the Northern granites

TABLE 6.1

AGE RELATIONS BETWEEN THE NORTHERN GRANITES

Ecuty Granite:	Cap de la Hague Granodiorite:
Isolated outcrop only seen to cut St. Martin monzonite. Contains inclusions of St. Martin monzonite.	Rafts of St. Germain granite found in Cap de la Hague granodiorite. Veins of Cap de la Hague granodiorite cut the following: St. Germain granite, La Becchue quartz diorite, Houffet granodiorite.
St. Germain Granite:	Locally veins La Becchue quartz diorite at contact. Single xenolith of ? La Becchue quartz diorite found in St. Germain granite.
La Becchue Quartz Diorite:	Contains rafts of Houffet granodiorite.
Houffet granodiorite:	Contains blocks of the agmatitic diorite.
Agmatitic Diorite	

St. Martin Monzonite	Sary Granodiorite
Cut and veined by St. Germain granite. Cut and veined by Ecuty granite.	Cut by veins of Cap de la Hague granodiorite.
Could be older than complete sequence of rocks given above. Relations with Sary granodiorite unknown.	Possibly older than complete sequence of rocks given above.

(see table 6.1).

The Cambrian sediments have been accepted as unconformably overlying the granites of the northern area (Graindor, 1960b). As the granites are post-tectonic it would seem reasonable to assume that they were intruded after the deformation affecting the Thiebot complex and before the deposition of the Cambrian sediments. The only radiometric age determinations are those of Leutwein (1968) who obtained an Rb/Sr single mineral date of 450 ± 20 m.y. for an orthoclase, a K/Ar mineral date of 340 ± 10 m.y. for an orthoclase and a K/Ar whole rock date of 530 ± 20 m.y., all on a rock sample from near Auderville. Because of their nature these determinations do not help in establishing the age of the intrusions.

The St. Martin Monzonite

This intrusion occupies most of the area lying behind the Anse St. Martin as far inland as Omonville-la-Petite and Digulleville. Exposure is poor and inland it is mainly confined to badly weathered road cuttings. However, on the coast at Havre de Plainvic it is possible to examine the rock in slightly more detail. An area to the east of Beaumont-Hague to beyond Gréville-Hague is also underlain by St. Martin monzonite. The extent of this area may be only guessed at by changes in topography as the number of actual outcrops is very limited and unweathered exposures were not found at all.

The relative age of the St. Martin monzonite may be established only within certain limits from the field relationships. It is clearly younger than the banded and augen gneisses of the Omonville area as rafts of these rocks may be seen to be included in the monzonite at Havre de Plainvic. Rafts of quartz dioritic gneiss may also be recognised within the monzonite but none may be unequivocally identified as Jardeheu quartz dioritic gneiss. The boundary between the

St. Martin monzonite and the gneisses of the Omonville area in Baie de Jardeheu is faulted. However, rafts of gneiss are more common, monzonite becomes more dioritic in appearance and the K-feldspar crystals become much smaller as the boundary is approached which suggests that this does represent something close to an original margin of the intrusion. At the same locality, Jardeheu quartz dioritic gneiss containing intruded sheets of Omonville streaky gneiss is seen now within 20 m of the monzonite but no Omonville streaky gneiss was found intruding the monzonite. This suggests, but does not prove, that the St. Martin monzonite may post-date the intrusion of the Omonville streaky gneiss.

Veins of the St. Germain granite may be seen to intrude the St. Martin monzonite on the west side of Anse St. Martin and the Ecuty granite both contains rafts of the monzonite and intrudes it with a series of veins. The St. Martin monzonite is older than the St. Germain and Ecuty granites, but unfortunately its age relationships with the other members of the Northern granites cannot be established. It is considered likely that the St. Martin monzonite is probably older than all the Northern granites, as it is older than the St. Germain granite and does not appear to fit into the sequence of intrusive phases making up the Northern granites. Thus, the monzonite is tentatively assigned as being intruded after the formation of the Omonville streaky gneisses but before the emplacement of the Northern granites.

Jérémine (1930) described the localities near La Brasserie and close to Beaumont-Hague, where the St. Martin monzonite may be seen to have Cambrian sediments above it. The nature of this relationship is discussed in Chapter 7. She also described how the Cambrian sandstones often contain abundant fragments of red K-feldspar and recorded finding a fragment of the rock with large microcline crystals within the Cambrian sandstone at the old quarry near Beaumont-Hague. On this evidence it would seem reasonable to assume that the St. Martin monzonite is Precambrian in age.

Throughout the main mass of the intrusion the St. Martin monzonite is seen as a light coloured, medium to coarse grained rock usually with K-feldspar megacrysts up to 4 cm long. It may sometimes contain inclusions of a finer grained green rock which are typically about 10 cm in diameter (see plate 6.1). They tend to have rounded margins and may contain metasomatic K-feldspar megacrysts. At Havre de Plainvic the St. Martin monzonite also occurs as a slightly finer grained rock without megacrysts and generally lacking in inclusions. It appears that the megacrystic phase veins the non-megacrystic phase. Contacts between the two phases are common (see plate 6.2). They are sharp and, within the megacrystic phase, megacrysts are often concentrated along the contact. They may be arranged in clusters in embayments of the contact or with their long axes either parallel or normal to the contact. The megacrysts are never truncated by the contact.

In thin section the megacrystic phase of the St. Martin monzonite is seen to be an inequigranular medium to coarse grained rock composed of about 50% plagioclase, megacrystic K-feldspar, only minor quartz (about 10%) and subsidiary hornblende, chlorite and biotite.

Plagioclase is oligoclase (An_{10}-An_{15}) in composition and occurs as euhedral crystals up to 4 mm in size. It is usually very altered and epidote may be developed in it. K-feldspar (20-30%) occurs predominantly as megacrysts typically 2 cm long. They usually show Carlsbad twinning and perthite is confined to thin films. Cross-hatch twinning is only rarely developed and even then rather patchily. The megacrysts often contain inclusions of small partly absorbed plagioclase grains. K-feldspar with cross-hatch twinning also occurs along grain boundaries and sometimes appears to replace plagioclase. Quartz (10-15%) is mainly interstitial, although there are some rare pools up to 2 mm in diameter. Some crystals are strained.

Hornblende (6-10%) tends to be euhedral and is seen as slightly poikilitic bladed grains up to 2 mm long and with included apatite, biotite and magnetite. It is pleochroic with α : light yellow, β : green, γ : dark green and γ : $c = 16^{o}$. In some sections it has been replaced by chlorite. Chlorite (3%) also occurs as discrete flakes up to 1.5 mm long with kinks in the cleavage. It contains inclusions of apatite needles and magnetite growing along the cleavage. Biotite, α : straw yellow, β , γ : olive green, occurs sporadically and allanite is an occasional accessory mineral.

The non-megacrystic phase contains about 50% plagioclase of the same composition (An_{10}-An_{15}) as in the megacrystic variety and slightly more quartz (about 20%). The K-feldspar is less abundant and occurs as small grains (1 mm) along grain boundaries and around plagioclase grains. Hornblende may occur in patches of small grains (0.5 mm) associated with apatite and magnetite as well as the larger (1-2 mm) slightly poikilitic prisms. Green biotite is slightly more abundant than in the megacrystic variety.

The green inclusions are fine grained and dominantly composed of an interlocking network of plagioclase and hornblende. Plagioclase (50-70%) is oligoclase (An_{10}-An_{15}) in composition. It occurs as euhedral grains about 0.2-0.6 mm in size with cloudy centres. Hornblende (18-28%), α : yellow-brown, β : green, γ : dark green, forms subhedral to ragged rather acicular grains 0.2 mm in size, although rare phenocrysts reach 1 mm. They are often twinned and have lobate crystal margins. K-feldspar (6-12%) tends to be interstitial or sometimes in clumps up to 2 mm across of several 0.3 mm grains. Other subsidiary minerals include small flakes of green biotite and rare pockets of quartz. Accessory minerals include apatite, sphene and epidote.

Although the St. Martin monzonite occupies a large area the lack of fresh exposures makes any detailed study difficult. Accordingly, modal and chemical analyses were confined to the outcrop at Havre de Plainvic and only one sample of each of the main phases was chemically analysed.

Jérémine (1924) did not recognise the non-megacrystic variety in her description of the intrusion. She considered that the green inclusions and the megacrystic phase must have originated by differentiation of the same magma at depth because of their mineralogical similarity. Certainly the very widespread presence of the inclusions throughout the intrusion must lend support to the suggestion that they may be genetically connected with the formation of the intrusion. The petrographic descriptions and the modal and chemical analyses shown in table 6.2 indicate that the megacrystic phase is more evolved than the green inclusions and that the non-megacrystic phase is the most evolved. The field relations indicate that the green inclusions and the non-megacrystic variety both pre-date the megacrystic phase. It is interesting to speculate that the megacrystic variety might result from reactions between the two earlier phases. The chemical composition of the megacrystic phase is very close to that which is obtained by simply mixing equal weights of materials with the same major element composition as the earlier phases. This is shown by the calculated mixture of table 6.2. However, the trace element composition of a mixture of this kind shows considerable difference from that of the megacrystic variety (see table 6.2), and the similarity

TABLE 6.2

MODAL AND CHEMICAL ANALYSES OF ROCKS FROM THE ST. MARTIN MONZONITE

	Green inclusions			Non-megacrystic		Megacrystic		
	704	76	81	668	163	664	999	86
Quartz	3.5	4.9	2.3	21.1	17.4	10.6	15.4	10.4
Plagioclase	71.2	50.0	68.8	57.2	48.1	56.6	48.7	32.2
K-feldspar	6.9	12.2	5.5	10.5	18.8	19.5	26.0	46.9
Hornblende	18.4	28.0	4.6	4.3	10.9	9.7	5.5	6.3
Biotite	-	2.1	-	6.7	3.2	1.7	-	-
Chlorite	-	0.1	-	-	1.2	0.9	3.2	3.1
Ore	-	1.3	1.6	0.1	0.4	0.8	0.8	1.1
Epidote	-	0.5	0.6	-	-	0.2	0.1	-
Apatite	-	1.0	-	0.1	-	-	0.3	-

	704	668	664	Mixture*		704	668	664	Mixture*
SiO_2	57.3	65.4	61.6	61.35	Rb	134	109	137	121
TiO_2	0.55	0.46	0.49	0.50	Ba	1248	1200	1643	1224
Al_2O_3	19.09	15.97	18.48	17.53	Pb	14	16	16	15
Fe_2O_3	2.53	1.12	1.8	1.82	Sr	1145	451	731	798
FeO	3.58	3.11	2.78	3.34	La	119	32	46	126
MnO	0.16	0.08	0.11	0.12	Ce	173	57	74	115
MgO	1.42	1.1	1.16	1.26	Nd	76	40	38	58
CaO	4.6	2.73	3.28	3.66	Y	22	15	12	19
Na_2O	4.38	4.15	4.3	4.26	Th	17	1.3	0.9	9
K_2O	4.84	3.6	4.95	4.22	U	4.1	0	0.6	2
P_2O_5	0.30	0.15	0.2	0.22	Zr	276	174	286	225
H_2O	0.84	1.26	1.02	1.05					
	99.59	99.13	100.17	99.33					

* Calculated mixture of equal weights of 668 and 704.

in the major element composition may be no more than coincidence.

The Sary Granodiorite

The Sary granodiorite has not been fitted into the intrusive sequence of the Northern granites. The occurrence of this granodiorite is extremely limited. It is seen at only two localities, Baie de Sary and Greniquet and on each occasion it is only about 100 m wide. It is important, however, because in both localities Cambrian sandstones rest unconformably upon it.

It is in direct contact, to the north, with the Cap de la Hague granodiorite. Neither rock shows a decrease in grain size close to the contact, but there are faint dark bands of mafic minerals developed in the Cap de la Hague granodiorite parallel to the contact. At Greniquet more conclusive evidence as to the age relations of the two rocks may be seen. A vein of Cap de la Hague granodiorite cuts the Sary granodiorite stoping off small fragments of it (see plate 6.6). Thus the Sary granodiorite is older than the Cap de la Hague granodiorite but its age relationship to the other rocks of the Northern granitic complex cannot be ascertained. It may only be noted that it shows considerable alteration and some deformation, and could conceivably be older than all of them. Accordingly, it is described before the sequence of Northern granites.

The Sary granodiorite is a medium to coarse grained rock with a dirty green sheared appearance where it is more intensely altered. In less altered parts the feldspar grains appear cream, green or red giving the rock a colourful appearance.

The Sary granodiorite is an inequigranular rock with a grain size varying between 1 and 4 mm and a colour index of 10. Plagioclase makes up more than 50% of the rock and quartz 25%. There is relatively minor K-feldspar and usually the principal mafic mineral is chlorite. The degree of deformation and alteration is variable, but often quite high, and calcite occurs as late alteration patches and veins.

Plagioclase (55%) may be up to 4 mm in grain size and is usually very altered. It is albitic in composition (An_4-An_8) and occurs as subhedral to anhedral grains with thin albite lamellae and some Carlsbad twinning. There are often signs of a later growth on the rims of the grains. Twin lamellae may be bent and dislocated by the later deformation. Quartz (about 25%) grains (1 mm) are usually in aggregates forming interstitial pockets up to 4 mm in size showing well developed strain lamellae. K-feldspar is variable in amount. It is poorly perthitic and mainly interstitial. It does occur as grains up to 3 mm in size with inclusions of small plagioclase crystals. Replacement by fine needles of albite takes place sporadically.

Chlorite (up to 8%) may be in large flakes up to 3 mm in size or aggregates of smaller grains. The aggregates have regular boundaries and may be pseudomorphs. The single flakes contain inclusions of quartz and ore minerals while their cleavage may show kink-bands and flectures. Chlorite is sometimes intergrown with small patches of K-feldspar. Biotite (up to 8%) grows in close association with chlorite aggregates and may be intergrown with chlorite along the cleavages. Calcite is present in the more altered parts of this granodiorite as thin veins and patches showing a late development.

The Agmatitic Diorite

The agmatitic diorite is the earliest recognised member of the Northern granite sequence. It is of very limited outcrop, being seen only on Nez Quilas and at the extremity of Les Roches du Houffet, not more than several hundred square metres in all.

On Nez Quilas the diorite is a melanocratic, fine grained massive rock and it is also seen in this form at the northern tip of Les Roches du Houffet. Towards the east, along the end of this peninsula, the meladiorite becomes agmatitic by the introduction of a leucocratic diorite which appears to form a network of veins breaking up the meladiorite (see plate 6.3). The veins range in thickness from 0.5 cm to 10 cm. The leucocratic diorite gradually assumes more importance until on the eastern side of the peninsula it is the dominant diorite with only rounded inclusions of meladiorite within it. Thus, within a 100 m the diorite has passed by a process of veining from a meladiorite to an agmatite and then into a leucocratic diorite with meladiorite inclusions.

The melanocratic diorite is a fine grained, equigranular holocrystalline rock with a mean grain size of 0.2-0.3 mm and a colour index of 60. It is normally unfoliated but a slight foliation may be produced by alignment of the hornblende prisms. The predominant minerals are hornblende and plagioclase with minor quartz. Biotite and chlorite are always present and may become locally more important. Both possibly form pseudomorphs after hornblende.

Plagioclase (about 33%) is present as anhedral grains (0.1-0.3 mm) of andesine (An_{38}-An_{44}). Albite twinning is sporadically developed with continuous lamellae and rarely pericline twinning is also seen. Continuous zoning is common in untwinned grains. The central portion of most grains is cloudy with alteration products of sericite and epidote. Hornblende (about 33%) forms stumpy, equidimensional crystals (0.1-0.5 mm) of euhedral to subhedral form. It is pleochroic with α: straw yellow, β: pale green, γ: green and γ: c = 14°. Simple and lamellar twinning are seen. Inclusions of apatite and quartz are found within the hornblende. Quartz (about 5%) is interstitial and anhedral in form. Biotite (about 10%) is present as plates (0.3-0.5 mm) with yellow to deep brown pleochroism, but also occurs as aggregates of smaller crystals or intergrown with chlorite. Chlorite (about 10%) is seen as aggregates of radiating or randomly orientated grains (0.1 mm) forming pseudomorphs after hornblende. It shows anomalous birefringence. Accessory minerals include apatite which is common throughout as fine needles and isolated grains of magnetite.

The leucocratic diorite is a medium grained, inequigranular, holocrystalline rock with a range in grain size from 0.1 mm to 4 mm and a colour index of 27. Plagioclase is the dominant mineral present with subsidiary hornblende and quartz. Biotite is only rarely present but chlorite may become important. Accessory minerals present are apatite and magnetite.

Plagioclase (about 60%) is seen as often tabular, euhedral to subhedral grains (1-2 mm) of andesine (An_{36}-An_{42}) composition. There is a large variation in grain size from 0.1 mm to 4 mm but the usual size is 1-2 mm. The grains are always very altered to sericite and epidote but thin albite lamellae and rare pericline twinning may be seen. Hornblende (about 20%) occurs as small crystals (0.3 mm), but more commonly there is a tendency for large bladed crystals to be developed up to 4 mm long and 1 mm wide. These are often poikilitic, enclosing rounded blebs of quartz, plagioclase and apatite and occasionally even smaller hornblende crystals. It is pleochroic, α : straw yellow, β : pale green, γ: green and extinction angle γ: c = 16° and simple twinning is fairly common. Quartz (about 10%) tends to be interstitial with irregular boundaries and grain size of up to 1 mm. It is often slightly strained. Biotite is rare but may be present locally. It forms flakes with yellow to light brown pleochroism, which often develop in aggregates together with skeletal ore minerals and epidote. Chlorite (6-10%) occurs as randomly arranged flakes (0.2 mm) in aggregates up to 1 mm in size and also as larger flakes (1-2 mm). It is pleochroic from straw yellow to green and exhibits anomolous birefringence. The aggregates are associated with epidote and ore minerals, and could be pseudomorphs after hornblende. Accessory apatite and magnetite occur throughout this rock.

The Houffet Granodiorite

This intrusion occurs between Pointe des Grouins in the west and Pointe de la Loge in the east. The contact between it and the St. Germain granite is parallel to the high water mark, with the Houffet granodiorite more or less confined to below high water. It encloses the agmatitic diorite on Nez Quilas and included blocks of agmatitic diorite are found in it at Les Roches du Houffet (see plate 6.4), confirming that it is younger than the agmatitic diorite. Especially in the vicinity of Les Roches du Houffet the granodiorite contains many rafts, up to several metres in diameter, of a very coarse biotite granite and a medium grained red granite. Basic xenoliths up to 25 cm in diameter are also found throughout the granodiorite.

The granodiorite is medium to coarse grained and pale in colour. It weathers to form a rough but rounded surface and has a poorly developed penetrative foliation formed by the elongation of the feldspars and alignment of the dark minerals.

The Houffet granodiorite is an inequigranular (1-4 mm) rock with a granitic texture and a colour index of about 10. The dominant mineral is plagioclase with subordinate quartz and chlorite. However, K-feldspar is nearly always present as a late mineral in amounts up to 10%.

Plagioclase (about 70%) forms interlocking crystals of 1-4 mm grain size. It is sodic andesine (An_{28}-An_{34}) in composition and usually extremely altered to sericite, muscovite and epidote. Albite twinning is not well developed and the twin lamellae are thin. Zoning is quite common. Occasionally, myrmekitic growths are developed at plagioclase-K-feldspar boundaries, but these are rare. Quartz (about 15%) forms pools up to 4 mm in diameter with a fairly circular cross-section and composed of smaller grains (1 mm) usually with simple boundaries. The quartz is often slightly strained. K-feldspar (about 6%) is interstitial. It contains fine, discontinuous, parallel perthitic films and irregular patches of replacement albite. It commonly forms around plagioclase grain boundaries and sometimes replaces it. There are some suggestions of cross-hatch twinning.

Biotite is not common but may occur as flakes (up to 3 mm) which are pleochroic from golden yellow to deep brown. The flakes contain apatite inclusions and are replaced by chlorite along the cleavage. Hornblende is rarely seen. It is a green variety and is usually at least partly replaced by chlorite. Chlorite (about 8%) occurs as single flakes, pleochroic from yellow to green, up to 3 mm long and with inclusions of epidote along the cleavages. It is also seen as aggregates of flakes associated with apatite, magnetite and epidote, which are probably pseudomorphs after hornblende. Apatite, epidote and sphene all occur as accessory minerals. Epidote may form replacive patches up to 3 mm wide and thin veins 0.3 mm wide and is obviously of late stage development.

<u>The La Becchue Quartz Diorite</u>

This rock outcrops between Nez Beyard and Les Roches du Houffet, a distance of about 1 km and also occurs in a small isolated mass included in the St. Germain granite on the west side of Havre de Bombec. At Nez Beyard it is cut by the younger Cap de la Hague granodiorite which also sends off thin dykes into it. It contains patches up to several metres long of Houffet granodiorite throughout its outcrop but especially near Pointe des Grouins. These may be shown to be included rafts as there is a decrease in grain-size in the quartz diorite adjacent to the granodiorite and, locally, the quartz diorite develops a foliation formed by the alignment of hornblende crystals which follow the margin of the Houffet granodiorite rafts. The slight foliation in the granodiorite rafts is oblique to the contact with the quartz diorite and cut off by it. Thus, on field evidence, the La Becchue quartz diorite is younger than the Houffet granodiorite and older than the Cap de la Hague granodiorite.

The La Becchue quartz diorite is a medium grained rock containing larger crystals of white or slightly orange plagioclase and euhedral hornblende in a greenish matrix of smaller crystals. Larger crystals of quartz are also common (see plate 6.5).

It is noticeable that the rock has undergone some deformation and the degree of cataclasis varies from place to place.

In thin-section it is seen to be an inequigranular (1-5 mm) rock with a porphyritic texture formed by the larger plagioclase, hornblende and quartz grains. It has a colour index of around 20.

Plagioclase is again the dominant mineral and large (4 mm) zoned grains are surrounded by smaller grains and interstitial quartz. Quartz also occurs in round pools and there are large euhedral hornblende prisms. Chlorite is mainly developed along grain boundaries.

Some specimens show the effects of deformation. Twin lamellae in plagioclase are bent, quartz strained and chlorite cleavage kinked. The deformation is not usually sufficiently intense to show a completely cataclastic texture.

Plagioclase (about 65%) occurs as larger crystals up to 4 mm in size and also as much smaller grains about 0.5 mm in size and has a composition on the oligoclase - andesine boundary (An_{28}-An_{34}). Oscillatory zoning is often present and sometimes the zoned crystals are untwinned. Albite twinning with thin, sometimes discontinuous twin lamellae is fairly common and some Carlsbad and pericline twinning also occurs. Alteration of the plagioclase is often intense. Quartz (15-20%) is both interstitial and in clear pools with few inclusions. These pools are often up to 4 mm in size and show late growth at the margins. Concentric bands of inclusions occur close to the margins and the quartz sends out fingers in between the surrounding mineral grains. Hornblende (about 5%) is seen as isolated euhedral grains of 2 mm size with a slight tendency to exhibit a poikilitic texture. It also occurs as much smaller grains associated with chlorite. Both are of the yellow-green variety with α : yellow, β : green, γ : deep green and extinction angle $\gamma : c = 15^{\circ}$. Chlorite (about 10%) occurs uniformly throughout the rock as small grains growing along grain boundaries of the other minerals and occasionally as large isolated flakes (2-3 mm) with ore minerals developed along the cleavages. Biotite has an uneven distribution and may be as high as 5% but is often absent. It is seen as flakes (0.5 mm), with golden yellow-deep brown pleochroism, growing in clumps along grain boundaries. It is altered to chlorite along cleavages. K-feldspar is a very minor constituent and shows a late replacive growth. It may sometimes be seen replacing plagioclase in small interconnected patches (0.3 mm) and at the edges of the grains. Sphene occurs as sporadic isolated granules (0.6 mm) and other accessory minerals are apatite, epidote and magnetite.

<u>The St. Germain Granite</u>

This granite outcrops from east of Port Racine at Pointe du Nez, westwards along the coast to Pointe de Houffet and again around Goury.

It is the principal granite type north of a line from Laye to Port Racine, an area of about 16 sq km. The only exception to this is cl to the west coast from Cap de la Hague to La Roche and as far inland as Auderville which is predominantly composed of Cap de la Hague grano diorite. The boundary between these two rock types can only be conjectural because of the scarcity of outcrops inland and the nature of the relationship between them.

Between Semaphore de la Hague and Goury, close to the headland on which an anemometer is situated, St. Germain granite occurs as rafts 5 to 10 m wide within the Cap de la Hague granodiorite. In detail, there is a faint foliation developed in the Cap de la Hague granodiorite closely parallel to the margins of the rafts, even where the granodiorite has formed small lobate fingers into the rafts. Any foliation seen in the St. Germain granite is oblique to the margins of the rafts. The Cap de la Hague granodiorite is, therefore, younger than the St. Germain granite.

About half way along the beach to Goury an isolated mass of St. Germain granite about 0.2 km wide occurs. There is a suggestion that the faint foliation in the Cap de la Hague granodiorite swings around to follow the contact with this large mass. Goury headland is composed of St. Germain granite, again probably surrounded by granodiorite. On the headland itself a much more delicate relation between the two rock types may be seen. Here there is a patch of granodiorite 40 m by 10 m within the granite. Close to this, stringers and bands of granodiorite, up to a metre long and 15 cm wide, are developed in the granite, giving a striped or patchy appearance but no decisive evidence could be seen as to whether these are included remnants or replacive patches. On the basis of the evidence mentioned previously it is more likely that these are replacive patches of Cap de la Hague granodiorite within the St. Germain granite.

From the foregoing description of granitic rafts and isolated masses, and of replacive patches of granodiorite, it is clear that the proposed boundary between the two rock types can only be tentative.

Between Semaphore de la Hague and Goury a single xenolith 10 cm in length of what appeared to be La Becchue quartz diorite was found in the St. Germain granite. At the eastern end of La Becchue diorite, on the beach near Pointe des Grouins, the St. Germain granite sends several thin (10 cm wide) veins into La Becchue quartz diorite at the contact. The St. Germain granite is, therefore, younger than La Becchue quartz diorite.

At Pointe du Nez east of Port Racine the contact between the St. Germain granite and the St. Martin monzonite is exposed. This shows veins of granite 30 cm wide cutting the monzonite and the St. Germain granite is clearly younger than the St. Martin monzonite.

The St. Germain granite is a medium to fine grained almost equigranular rock. K-feldspar is usually orange in colour and together with slightly milky-white rounded quartz grains both stand out from a matrix of creamy coloured plagioclase and evenly distributed dark biotite flakes. It weathers to an orange-brown colour but becomes greener where it has suffered cataclasis. Inland, it is usually a soft, decomposed rock with dark flakes of mica in it.

Deformation of the St. Germain granite is intense in the Port Racine area and has given rise to extremely cataclased rocks. Elsewhere, bands of localised deformation about 25 cm wide also occur. These trend very approximately in a north-south direction.

The St. Germain granite has a grain size variation of 1 to 3 mm in most samples and a colour index of between 4 and 8. It shows two characteristic textures. In the first, which is by far the more common, the grain size of all the minerals is more or less equal and quartz may tend to be dominant, surrounding euhedral plagioclase and K-feldspar. The other texture has only been found in some samples from Goury headland and from the quarry south of Danneville. There is no evidence that it constitutes a separate granite type. This texture shows a groundmass (0.2 mm) of quartz and K-feldspar which is overgrown by crystals (up to 3 mm) of plagioclase, quartz and K-feldspar, all showing zones of concentric inclusions and growth of later rims.

A further feature of the St. Germain granite is the replacement of K-feldspar by an intergrowth of fine pointed needles of albite crystals. This replacement may be absent, partial, or virtually complete so that all that remains are albite pseudomorphs of K-feldspar still showing Carlsbad or Baveno twinning (see plate 6.10). Around Port Racine, from Pointe du Nez to west of Les Herbeuses, the St. Germain granite has suffered strong deformation. Samples show a variety of cataclastic textures ranging from a slight breakdown where the larger clasts (2-3 mm) are bordered by small fragments, to complete breakdown where the entire rock is composed of tiny mineral fragments and the component minerals can no longer be identified because of their fine grain size. In the less deformed rocks (see figure 6.11) plagioclase twin lamellae are bent and displaced by microfractures and some strain lamellae are produced. Sometimes, the larger fragments appear to have been pushed together and thin films of chlorite are developed at grain boundaries. K-feldspar is often severely deformed and fractured, with chlorite growing along the fractures. Quartz is broken down into small grains with strain lamellae and there is noticeably less recognisable quartz than in the undeformed granite, probably because it has readily broken down to very fine fragments at an early stage.

Plagioclase in the undeformed granite usually makes up between 30 and 40% of the rock but may rise to 50%, as is found along La Loge beach section. This is a result of replacement of K-feldspar by albite and there is a corresponding drop in K-feldspar content.

The plagioclase composition is albite-oligoclase (An_5-An_{14}). It ranges in grain size from 1 to 2 mm and is usually subhedral. Albite twinning is not always well developed and there are occasional Carlsbad and rare pericline twins. In some grains a complex patchwork of albite twinning is seen, as if a number of smaller grains of plagioclase with random orientation have grown together to form one larger grain but retaining their original albite twinning. Some slight oscillatory zoning may be observed and grains often show a thin (0.1 mm) rim of clear albite giving rise to more irregular slightly lobate grain boundaries.

Quartz (about 35%) is interstitial and in rounded pools up to 4 mm in diameter. It is usually only slightly strained. In the granite samples that show a finer groundmass, the larger pools of quartz have a later growth around their margins whilst that in the groundmass often shows triple point grain boundaries.

K-feldspar is usually around 20% by volume of the rock but may fall as low as 3% where it has been extensively replaced by albite. It ranges from euhedral grains of about 3 mm in size, often almost square in section, to interstitial patches. Vein perthite is fairly well developed and some braided perthite may also be seen. Carlsbad twinning is common sometimes combined to give interpenetrant forms and some Baveno twinning also occurs. The larger crystals usually contain inclusions of small (up to 0.3 mm) quartz and plagioclase blebs which appear rounded. They may have a completely random orientation or they may, especially in the samples with a finer matrix, be arranged in zones. Some crystals show randomly orientated inclusions in a zone which occupies the central third of the crystal. More usually, the inclusions occupy a thin concentric zone at about one third of the distance from the centre to the margin, or sometimes just close to the margins. K-feldspar may be partially or almost completely replaced by fine tapering needles of albite. Albite pseudomorphs after K-feldspar still show Carlsbad or Baveno twinning and have a fine chequered appearance formed by the individual albite crystals (see plate 6.10).

Biotite (0-4%) is usually seen as laths up to 1.5 mm long full of magnetite inclusions and sometimes altering to chlorite. It also occurs as interstitial felts of smaller flakes. All the biotite exhibits pale yellow to green pleochroism. Chlorite (usually about 4%) varies from randomly distributed small (0.5 mm) flakes growing along grain boundaries to larger (1.5 mm) aggregates or single flakes intergrown with magnetite. Muscovite may occur as an accessory mineral as small flakes (0.5 mm) within plagioclase. Other accessory minerals are magnetite and epidote.

The Cap de la Hague Granodiorite

The Cap de la Hague granodiorite forms the headland of Cap de la Hague from Nez Bayard to Goury. It also occurs south of Goury along La Roche beach to Greniquet. It is not possible to determine the exact extent of this rock inland because of poor exposure but it certainly occurs as far inland as Auderville and probably occupies most of the area from Semaphore de la Hague through Auderville to La Roche, with the exception of Goury headland.

The relations between the Cap de la Hague granodiorite and the St. Germain granite have already been discussed in detail and it was concluded that the Cap de la Hague granodiorite is younger than the St. Germain granite. It has also been shown to be younger than the Sary granodiorite.

At Nez Bayard the Cap de la Hague granodiorite is in contact with the La Becchue quartz diorite. It cuts across rafts of Houffet granodiorite within the quartz diorite. Sharp cross-cutting veins of Cap de la Hague granodiorite can be found in both the La Becchue quartz diorite and the Houffet granodiorite and it is younger than both these rocks. Thus the Cap de la Hague granodiorite could be the youngest member of the Northern granite complex. The only rock that may be of the same age or younger is the Ecuty granite but this cannot be decided on field evidence because the Ecuty granite is only seen in contact with the St. Martin monzonite and is not found in contact with any of the other Northern granites.

The Cap de la Hague granodiorite is essentially a medium to fine equigranular rock but contains occasional plagioclase phenocrysts which may be about three to four times the average grain size. Weathered surfaces are smooth and greenish in colour. Quartz does not stand out so much from the other minerals as in the St. Germain granite.

In thin-section the Cap de la Hague granodiorite is seen to have a mean grain-size of 1-2 mm and a colour index of slightly less than 10. Interlocking euhedral plagioclase makes up 50% of the rock and quartz about 30%. K-feldspar is always present and frequently interstitial but it is usually less than 10% of the total feldspar, making this a K-feldspar poor granodiorite. Cataclastic textures of varying intensity are developed in some specimens from zones of local deformation. Fine veins (0.2 mm) of albite are not uncommon throughout the rock and these appear to be post-deformational.

Plagioclase (about 53%) forms subhedral to euhedral grains

(1-2 mm) of albite-oligoclase (An_7-An_{14}) composition. Some normal and oscillatory zoning is seen and both albite and Carlsbad twinning occur together with noticeable pericline twinning. Patchy replacement by radiating aggregates of albite has taken place in some grains. Quartz (about 30%) occurs as rounded or euhedral grains up to 1.5 mm in size and also interstitially. K-feldspar (about 4%) is a very subordinate component of the rock and is developed along grain boundaries, especially around quartz. It is perthitic and is sometimes replaced by needles of albite. Biotite (0-4%) is variable in amount. Flakes (0.5 mm) show yellow to green pleochroism and tend to grow in radiating sheaves sometimes associated with muscovite or replaced by chlorite. Muscovite (1.5%) although a minor constituent is a characteristic feature of this rock. It is randomly developed in flakes up to 0.5 mm in size sometimes replacing plagioclase.

The Ecuty Granite

The Ecuty granite forms the headland west of Baie de Jardeheu and extends westwards into Anse St. Martin to Havre de Plainvic, a distance of nearly 1 km. It probably also makes up some of the off-shore islets. East and west of Omonville-la-Petite the Ecuty granite forms the sides of the valley but it is not possible to determine its relationship with the nearby St. Germain granite.

Contacts with the St. Martin monzonite are frequent. Dykes from the granite cut the monzonite and blocks of the monzonite are included in the granite. There is no doubt that the Ecuty granite is younger than the monzonite. Unfortunately the Ecuty granite is not seen in contact with any other rocks so that its age relations with the other rocks of the Northern granitic complex cannot be established from field evidence.

The granite is a medium grained rock with a red colouration. It weathers to give a rough, gritty, quartzose surface and has an angular appearance as the result of its well developed joining. There is a variation in the intensity of the red colouration. For the last few hundred metres to the western boundary it becomes generally paler although patches several metres in extent of a deeper colour do occur.

On the west side of Baie d'Ecuty a pegmatite runs along the contact between the Ecuty granite and the St. Martin monzonite for about 20 m (see figure 6.7). It is made up of a coarse red feldspar matrix in which pods of milky-white quartz up to 50 cm in diameter occur. Small needles of hornblende are found in thin lenses up to 15 cm long. Small inclusions of St. Martin monzonite are caught up in the pegmatite and it is clearly associated with the Ecuty granite rather than the monzonite.

Towards its margins the Ecuty granite often becomes a smoother, finer grained rock but with pockets up to 10 cm in size containing coarser quartz and K-feldspar within them. These pegmatitic pockets have very irregular margins and are sporadic in their distribution.

Besides included rafts of St. Martin monzonite the Ecuty granite also contains included blocks of a granitic gneiss in various stages of assimilation. They are usually of the order of a metre in size and no more than vague remnants but one inclusion in the headland west of Baie de Jardeheu is about 30 m long and 5 m high. It has a banded appearance and has been veined by small lobes of granite following the banding.

In the Baie de Jardeheu a series of finer grained red dykes come off from the granite. They may be up to 20 m wide and have sharp contacts with the rocks they intrude, both St. Martin monzonite and Jardeheu quartz dioritic gneiss. They sometimes develop a spheroidal texture but are otherwise quite massive.

In some places, for example the small bay at the headland west of Baie d'Ecuty, the Ecuty granite shows a fairly strong cataclastic deformation and a prominent surface has been developed parallel to it. The direction of this surface varies between 70° and 150°E of N and dips at 60° N or NE.

The Ecuty granite is a medium grained granitic rock with a grain size range from 1 to 5 mm and a very low colour index of less than 4. The three main minerals, strongly perthitic K-feldspar, plagioclase and quartz are in roughly equal proportions but there is always slightly more K-feldspar than plagioclase.

Plagioclase (20-30%) usually forms crystals of 1 to 2 mm in size, slightly smaller than the usual grain size of the rock. They are albite-oligoclase in composition (An_8-An_{14}), anhedral, and show thin, discontinuous albite lamellae and some Carlsbad and pericline twinning. They may be slightly zoned and are often altered.

K-feldspar (30-40%) forms anhedral grains up to 4 mm in size often with irregular grain boundaries. It is strongly perthitic with braided, ribbon and vein perthite all prominent. The perthitic veinlets may show albite twinning and there is also some replacement by patch perthite. Both Carlsbad and Baveno twinning is common. Cross-hatch microcline twinning is not usual but some crystals do show it on a fine scale. The K-feldspar grains have often grown into contact with each other and reaction rims of albite and fine inclusions occur at these boundaries. Inclusions of small (0.2 mm) partly rounded plagioclase crystals similar in composition to the other plagioclase in the rock are quite common within the K-feldspar and these have clear albitic rims.

Quartz (30-40%) is interstitial or in aggregates (up to 5 mm) of grains sometimes including small plagioclase or K-feldspar crystals. These aggregates may be in fairly straight edged contact with the surrounding grains. Occasionally, stringers of K-feldspar follow grain boundaries within the quartz aggregates. The quartz may show undulose extinction.

Biotite (about 2%) forms sparse green flakes up to 1 mm long usually with inclusions of ore minerals. Chlorite (0-1%) may occur as rare radiating clusters of fibres. Both biotite and chlorite are developed along grain boundaries but they also occur in rare pockets with regular outlines, intergrown with magnetite and apatite.

Towards the margins of this granite marked graphic intergrowth, principally between K-feldspar and quartz, is developed and more rarely between plagioclase and quartz. Plagioclase, where it is in contact with quartz, often shows corroded boundaries having embayed and lobate margins. Rarely, rounded plagioclase grains may be entirely surrounded by a graphic intergrowth of quartz and K-feldspar.

Towards its western margin the Ecuty granite loses its red colour and looks more like the St. Germain granite in hand specimen. A series of samples representing the gradation from this paler coloured rock into the redder rock were carefully examined. Although so much paler in colour, no difference in mineral composition or texture could be distinguished between the lighter coloured granite and the red coloured Ecuty granite. It was concluded that despite the considerable difference in colour all the samples belonged to the same rock-type.

Summary of Field Relations and Petrography

On the basis of field evidence the Northern granitic rocks have been divided into six phases with the age relations between them as shown in table 6.1. That is, from oldest to youngest, agmatitic diorite, Houffet granodiorite, La Becchue quartz diorite, St. Germain granite and Cap de la Hague granodiorite. The Ecuty granite may be the youngest intrusive phase. It is probably younger than the

St. Germain granite but its relationship to the Cap de la Hague granodiorite is not known.

The St. Martin monzonite is older than the St. Germain granite and is probably older than all the Northern granites but there is no field evidence on this point. The age of the Sary granodiorite is uncertain and it is considered here as possibly older than the Northern granites.

Each of the phases of the Northern granites recognised in the field also shows its own characteristic textures and mineralogical composition as outlined in the petrographic descriptions (summarised in table 6.3) and defined by the modal analyses in table 6.4. Together they appear to constitute a series showing systematic variations in mineral composition. However, these variations usually have a much more regular form if the series is considered to have the order: agmatitic diorite, La Becchue quartz diorite, Houffet granodiorite, Cap de la Hague granodiorite, St. Germain granite, Ecuty granite.

Throughout this series so ordered there is a general increase in quartz and K-feldspar content. The first three members show a slight increase in plagioclase and the last three a decrease. The first three contain decreasing proportions of hornblende whilst the last three contain no hornblende at all.

There is an overall decrease in the colour index and in the proportion of the total feldspar that is plagioclase throughout the series (see figure 6.2B). The plagioclase composition varies from calcic andesine to sodic andesine and then to sodic oligoclase.

In all the rocks there is at least some alteration of the mafic minerals to chlorite. This is more complete in the more acid members where the mafic content is low. Plagioclase is often partly altered to sericite. Muscovite is sometimes developed as a late mineral.

A plot on a triangular diagram of the modal percentage of quartz,

	Meladiorite	Leucodiorite	Houffet Granodiorite	La Becchue quartz diorite	St. Germain granite	Cap de la Hague Granodiorite	Ecuty granite
Quartz	5% interstitial	10% interstitial	15% rounded pools	15-20% pools and interstitial	35% pools and interstitial	30%	30-40%
Plagioclase	33% An_{38-44} Continuous zoning	60% An_{36-42} large variation in grain size. altered	Up to 70% An_{28-34} very altered	65% An_{28-34} oscillatory zoning altered	30-40% An_{5-14} rims of clear albite	50% An_{7-14}	20-30% An_{8-14}
K-feldspar	Not present	Not present	6% interstitial perthite - fine. Grows on plagioclase. grain boundaries.	Very minor late replacive growth.	20% perthitic replaced by albite. Simple twinning.	4% along grain boundaries, perthitic. replaced by albite.	30-40% strongly perthitic rare cross-hatch twinning.
Hornblende	33%	20% poikilitic	rare	5% porphyritic poikilitic	-	-	-
Biotite	10% brown	rare. Associated with magnetite, epidote.	rare large flakes brown	Up to 5% sporadic brown	0-4% altered to chlorite green	0-4%	0-3% altered to chlorite
Chlorite	10% replacing hornblende	6-10%	About 8%	10% large flakes small grains along grain boundaries	4% inclusions of magnetite	1-7%	associated with biotite
Others	apatite magnetite	apatite magnetite	apatite epidote sphene	apatite epidote sphene	muscovite magnetite	muscovite	magnetite

TABLE 6.3

SUMMARY OF PETROGRAPHY OF THE NORTHERN GRANITES

TABLE 6.4

MODAL ANALYSES OF THE NORTHERN GRANITES

	Meladiorite	Leucodiorite		La Becchue quartz diorite			Houffet granodiorite		
	91	98	101	61	457	465	69	407	188
Quartz	6.7	11.9	11.7	15.3	21.1	14.3	14.3	14.1	17.3
Plagioclase	36.6	63.9	54.1	63.1	58.1	68.7	70.0	70.9	64.8
K-feldspar	-	-	-	0.4	1.3	0.7	9.5	5.5	6.4
Hornblende	34.8	16.6	21.2	7.6	1.8	4.7	Trace	Trace	Trace
Biotite	9.3	-	1.2	-	5.0	0.8	-	0.2	2.4
Chlorite	8.7	6.4	10.7	12.2	11.5	8.8	5.3	8.3	8.1
Ore	1.0	0.1	0.2	0.3	0.2	0.7	0.9	0.1	0.7
Epidote	0.8	0.3	0.6	0.4	0.5	0.5	-	0.6	0.1
Apatite	2.2	0.8	0.2	0.8	-	0.5	-	0.3	0.1
Sphene	-	-	-	0.1	-	0.4	-	0.1	0.1
Muscovite	-	-	-	-	-	-	-	-	-
Q	15.5	15.7	17.8	19.4	26.2	17.1	15.2	15.6	19.5
P	84.5	84.3	82.2	80.0	72.1	82.1	74.6	78.3	73.2
A	0	0	0	0.5	1.6	0.8	10.1	6.1	7.2
F	100	100	100	99.4	97.8	99.0	88.1	92.8	91.0
M	56.8	24.2	33.9	21.4	19.0	16.4	6.2	9.6	11.4
Counts	1305	1199	1200	2017	2200	2220	2073	2405	2405

	Cap de la Hague granodiorite						St. Germain granite		
	37	10	32	192	9914	358	229	233	228
Quartz	34.0	27.5	31.0	32.8	29.1	28.1	28.0	36.2	34.7
Plagioclase	53.1	53.5	52.8	52.9	62.4	50.8	40.3	33.4	45.0
K-feldspar	3.5	11.1	5.6	3.9	2.5	1.9	24.1	26.1	15.3
Biotite	-	-	-	2.4	4.1	0.8	-	-	1.6
Chlorite	6.9	6.4	6.8	4.8	1.1	1.0	7.1	3.5	1.7
Ore	1.1	0.3	-	0.4	0.5	0.1	0.1	0.2	0.2
Muscovite	1.5	1.1	3.8	2.8	0.4	0.2	0.1	0.2	1.4
Q	37.5	29.9	34.7	36.6	31.0	34.8	30.3	37.8	36.5
P	58.6	58.1	59.1	59.0	66.4	62.8	43.6	34.9	47.4
A	3.9	12.1	6.3	4.4	2.7	2.4	26.1	27.3	16.1
F	93.8	82.8	90.4	93.1	96.0	96.4	62.1	56.1	74.6
M	9.5	7.8	10.6	10.4	6.1	2.1	7.6	4.2	4.9
Counts	1326	1210	1219	1241	2392	2054	1373	1291	2444

TABLE 6.4
(Continued)

MODAL ANALYSES OF THE NORTHERN GRANITES

St. Germain granite

	265	231	403	191	107	109	29	30	9915	39
Quartz	31.7	38.6	34.4	40.5	35.2	36.8	36.4	38.6	34.0	30.4
Plagioclase	36.3	42.4	47.5	48.3	50.2	52.1	29.4	35.6	44.1	40.1
K-feldspar	24.9	14.8	14.2	6.4	5.9	3.2	29.4	20.8	17.7	20.8
Biotite	4.4	-	0.4	1.0	1.9	0.4	-	-	2.3	4.4
Chlorite	1.8	3.5	3.0	3.5	5.3	7.1	4.5	3.9	1.6	4.3
Ore	0.5	0.5	0.4	0.3	0.3	0.4	0.3	0.3	0.3	-
Muscovite	0.4	0.1	0.1	-	-	-	0.2	0.7	-	-
Q	34.1	40.3	35.8	42.5	38.6	40.0	38.3	40.6	35.5	33.3
P	39.1	44.3	49.4	50.7	54.9	56.5	30.9	37.5	46.0	43.9
A	26.8	15.4	14.8	6.7	6.5	3.5	30.7	21.9	18.5	22.8
F	59.3	74.2	76.9	88.4	89.9	94.3	50.2	63.1	71.4	65.8
M	7.1	4.1	3.9	4.8	8.7	7.9	5.0	4.9	4.2	8.7
Counts	2334	2811	2690	2530	2972	2985	1212	1276	2752	1260

Ecuty granite

	167	995	257	174	171	168	432	434	669	728	670
Quartz	41.0	30.5	33.6	33.4	33.1	38.5	30.0	34.6	40.5	36.3	44.8
Plagio-clase	28.8	27.7	20.4	22.0	21.9	28.2	30.4	30.1	27.4	29.2	17.1
K-feldspar	29.5	40.3	42.5	41.5	41.7	30.2	36.0	31.4	27.7	32.2	35.3
Biotite	0.1	1.5	2.7	2.3	0.9	1.8	2.4	3.4	2.1	Trace	1.5
Chlorite	0.4	-	0.7	0.1	0.7	1.1	1.0	0.3	2.3	Trace	0.7
Ore	0.2	0.1	0.2	0.6	1.6	0.2	0.1	0.2	Trace	2.1	0.5
Q	41.3	31.0	34.8	34.5	34.2	39.7	31.1	36.0	42.4	37.2	46.1
P	29.0	28.1	21.1	22.7	22.6	29.1	31.5	31.3	28.7	29.9	17.6
A	29.7	40.9	44.1	42.8	43.1	31.2	37.3	32.7	29.0	32.9	36.3
F	49.4	40.8	32.4	34.7	34.4	48.3	45.8	48.9	49.8	47.6	32.7
M	0.7	1.6	3.4	3.0	3.2	3.1	3.7	3.9	4.4	2.1	2.7
Counts	2613	2514	1279	1444	1521	1279	2502	2688	2123	1832	1487

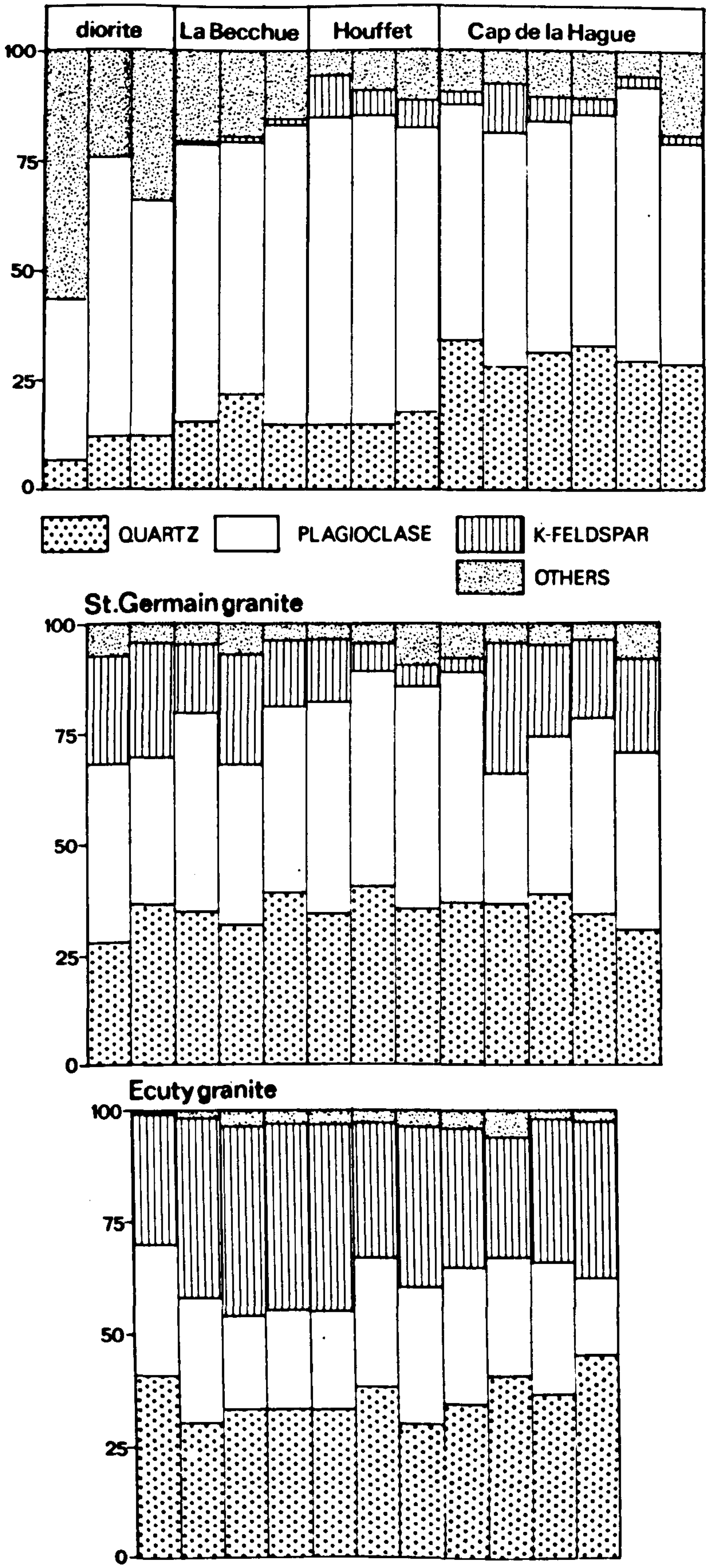
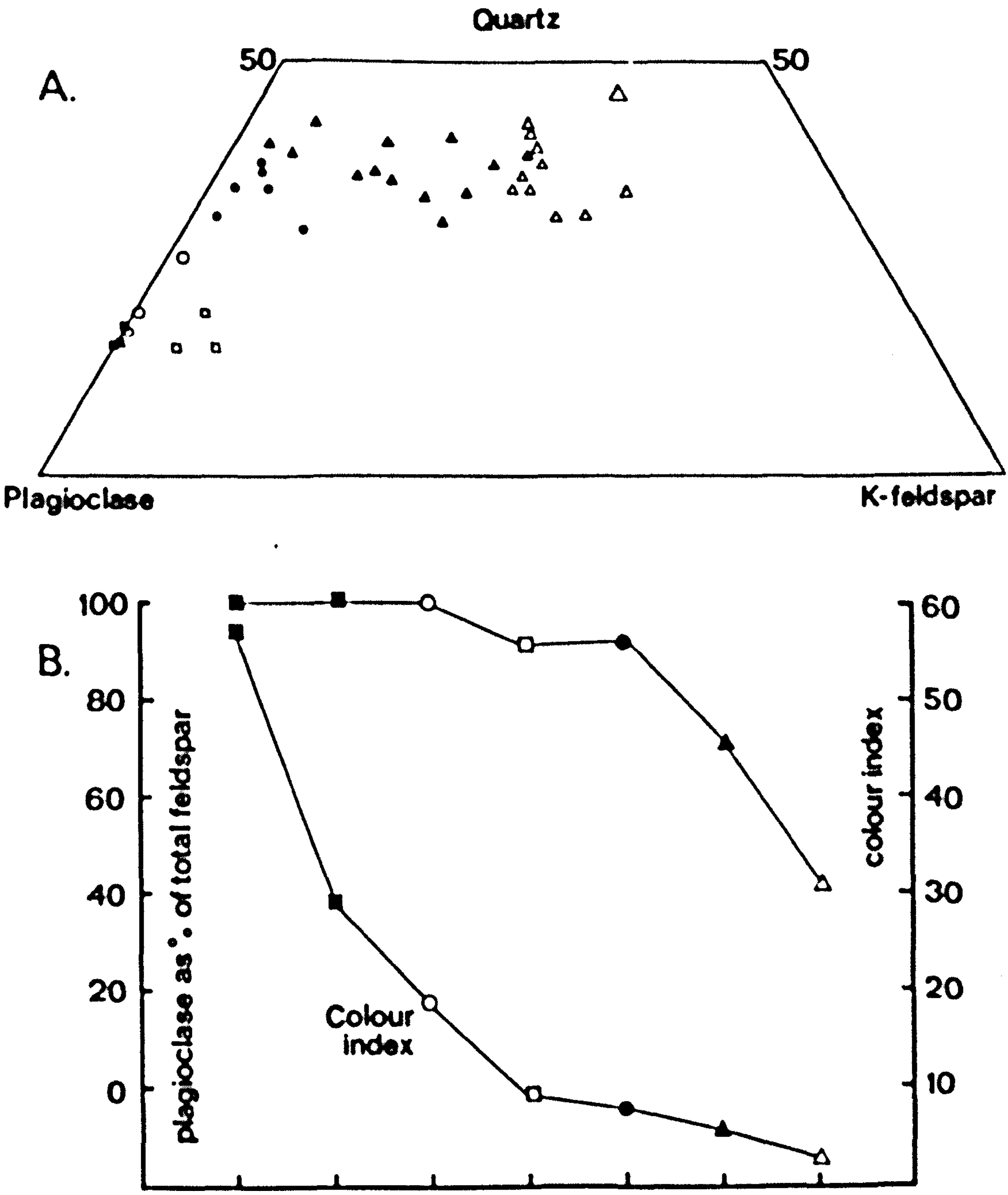


Fig.6.1 - Modal analyses of the Northern granites.



■ agmatic diorite
○ La Becchue quartz diorite
□ Houffet granodiorite
● Cap de la Hague granodiorite
▲ St. Germain granite
△ Ecuty granite

Fig. 6.2. Northern Granites.

A. quartz – plagioclase – K-feldspar plot.

B. percentage of feldspar plagioclase and colour index variation plots.

plagioclase and K-feldspar, recalculated to 100 per cent for all the modal analyses of the Northern granites shows a general trend (see figure 6.2A). The rocks of each phase with the exception of those from the St. Germain granite plot close together showing the general homogeneity within each phase. Those from the St. Germain granite show some spread because of the variation in the replacement of K-feldspar by albite. The order of the points on the trend is similar to that for the compositional series of phases rather than that based on the relative ages of the phases from field evidence.

<u>The Variation in Structural State of the K-feldspars of the Northern Granites</u>

The cell parameters of the phases present in a number of K-feldspar mineral separates from rock samples of the St. Germain granite, the Cap de la Hague granodiorite and the Ecuty granite were determined by X-ray powder diffraction techniques. Details of the method used are given in the Appendix. The results are presented in tables 6.5, 6.6 and 6.7 and the localities from which the samples were collected are shown in the sketch map of figure 6.3.

The samples from the St. Germain granite usually contain both monoclinic and triclinic phases, although in two samples from Goury only a triclinic phase was detected. The triclinic phases of different samples show a range of structural states from intermediate microcline to near maximum microcline. Samples from both the Cap de la Hague granodiorite and from the Ecuty granite only show a single triclinic phase present. From their position on the b - c diagram (figure 6.4A), their obliquity and from their position on an $\alpha^* - \gamma^*$ plot (figure 6.4C) these may be described as tending towards maximum microcline.

Many of the K-feldspars have anomalous 'a' values (Wright and

Sample Number	a	b	c	α	β	γ	V	Δ	Cr%	n	Comments
265M	8.599 0.017	12.932 0.008	7.201 0.003	90.0 -	115.91 0.11	90.0 -	720.2	0.0	90.8	9	Broad ill-defined 131 peak area.
265T	8.564 0.012	12.941 0.006	7.203 0.002	90.75 0.07	115.91 0.07	88.03 0.19	717.6	0.66	84.7	9	
371M	8.611 0.015	12.967 0.007	7.212 0.002	90.0 -	116.04 0.09	90.0 -	723.5	0.0	98.6	10	Well resolved 131 peak area. Possibly triclinic phase slightly dominant.
371T	8.615 0.010	12.970 0.005	7.212 0.002	88.95 0.06	115.95 0.06	89.75 0.18	724.4	0.84	100	10	
233M	8.633 0.019	12.981 0.009	7.200 0.003	90.0	115.88 0.11	90.0	726.0	0.0	100	10	Both phases clearly present, probably in equal proportions.
233T	8.647 0.005	12.996 0.003	7.201 0.001	91.59 0.04	115.95 0.03	87.05 0.12	726.7	0.74	100	8	
228T	8.505 0.012	12.984 0.006	7.202 0.002	91.09 0.05	115.87 0.07	88.07 0.15	715.3	0.43	79.3	9	Possibly monoclinic phase also present.
231M	8.630 0.019	12.974 0.010	7.192 0.004	90.0	115.93 0.14	90.0	724.2	0.0	100	11	131 peaks not well resolved. Equal proportions of each phase?
231T	8.560 0.009	12.987 0.005	7.214 0.002	91.28 0.05	116.11 0.05	87.73 0.15	719.5	0.51	89.2	9	

TABLE 6.5

CELL PARAMETERS FOR ALKALI FELDSPARS FROM THE ST. GERMAIN GRANITE

Sample Number	a	b	c	α	β	γ	V	Δ	Or%	n	Comments
452M	8.638 0.013	12.958 0.008	7.198 0.003	90.0	115.71 0.09	90.0	726.0	0.0	100	10	Both phases well resolved 131 peaks.
452T	8.609 0.007	12.967 0.004	7.199 0.001	90.89 0.06	116.12 0.04	87.80 0.16	721.0	0.73	92.7	8	Probably equal proportions each phase.
378T	8.571 0.001	12.952 0.000	7.215 0.000	90.51 0.01	116.03 0.01	87.90 0.02	719.3	0.75	88.7	7	131 peaks broad.
9916T	8.587 0.015	12.947 0.006	7.210 0.002	90.50 0.07	116.04 0.08	87.98 0.19	719.8	0.91	89.9	9	131 peaks fairly broad.
9915M	8.615 0.016	12.971 0.010	7.186 0.003	90.0	115.49 0.13	90.0	724.8	0.0	100	9	131 Monoclinic not well resolved.
9915T	8.576 0.019	12.973 0.012	7.204 0.004	90.73 0.10	116.46 0.13	88.45 0.30	717.3	0.56	84.0	10	Triclinic phase dominant?
9914T	8.520 0.018	12.969 0.006	7.212 0.002	90.58 0.05	115.93 0.10	88.26 0.16	716.3	0.64	81.7	10	131 peaks sharply separated.
450T	8.636 0.012	12.953 0.007	7.209 0.002	90.09 0.05	115.90 0.09	89.50 0.12	725.4	0.29	100	12	131 peak area broad peaks not well resolved.
188T	8.624 0.006	12.959 0.003	7.199 0.001	89.21 0.04	115.82 0.03	90.17 0.14	724.1	0.4	100	9	131 peak area complex.

TABLE 6.6

CELL PARAMETERS FOR ALKALI FELDSPARS FROM THE ST. GERMAIN GRANITE, THE CAP DE LA HAGUE GRANODIORITE AND THE HOUFFET GRANODIORITE

Sample Number	a	b	c	α	β	γ	V	Δ	Or%	n	Comments
991T	8.617 0.011	12.958 0.005	7.212 0.002	89.88 0.08	115.74 0.07	89.17 0.27	725.3	0.58	100	8	131 peaks slightly broadened.
993T	8.571 0.007	12.961 0.003	7.211 0.001	90.59 0.03	115.94 0.04	88.13 0.09	720.0	0.73	90.4	10	131 good sharp peaks.
167T	8.567 0.009	12.967 0.006	7.204 0.002	90.98 0.06	116.03 0.06	87.61 0.19	718.4	0.80	86.6	11	" "
994T	8.573 0.010	12.959 0.005	7.212 0.002	90.58 0.07	115.77 0.06	87.96 0.21	721.1	0.84	93.0	10	Perthitic albite also resolved.
995T	8.541 0.014	12.961 0.008	7.209 0.003	90.67 0.07	116.06 0.09	88.14 0.19	716.6	0.71	82.4	12	131-$1\bar{3}1$ sharp, well resolved peaks.
175T*	8.570 0.007	12.941 0.004	7.193 0.001	90.52 0.03	115.77 0.05	88.84 0.07	718.2	0.35	86.1	10	131-$1\bar{3}1$ poorly resolved broad peak area.

* Alkali feldspar from gneiss included in the Ecuty granite.

TABLE 6.7

CELL PARAMETERS FOR ALKALI FELDSPARS FROM THE ECUTY GRANITE

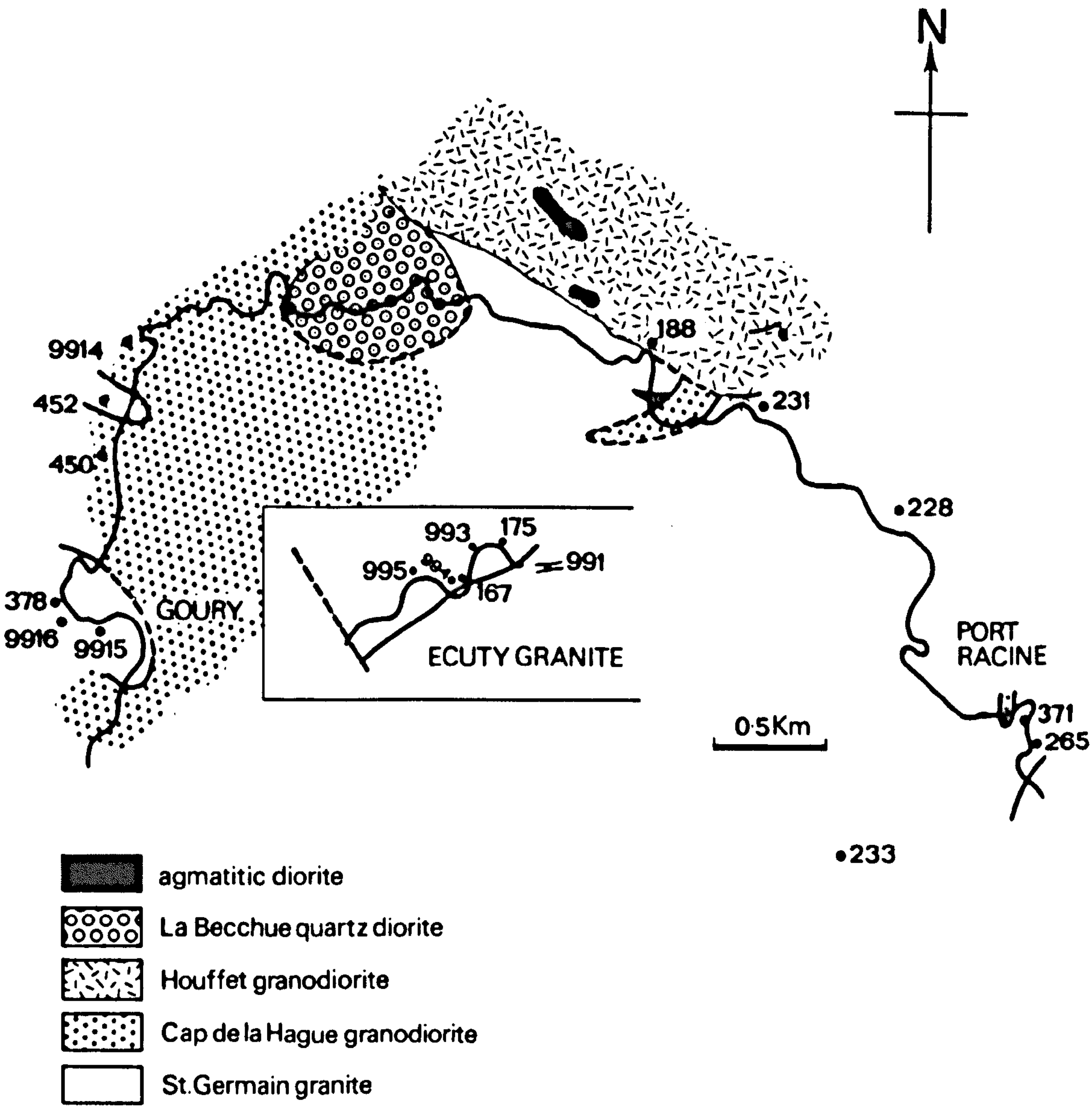


Fig. 6.3. Northern granites, K-feldspar sample localities

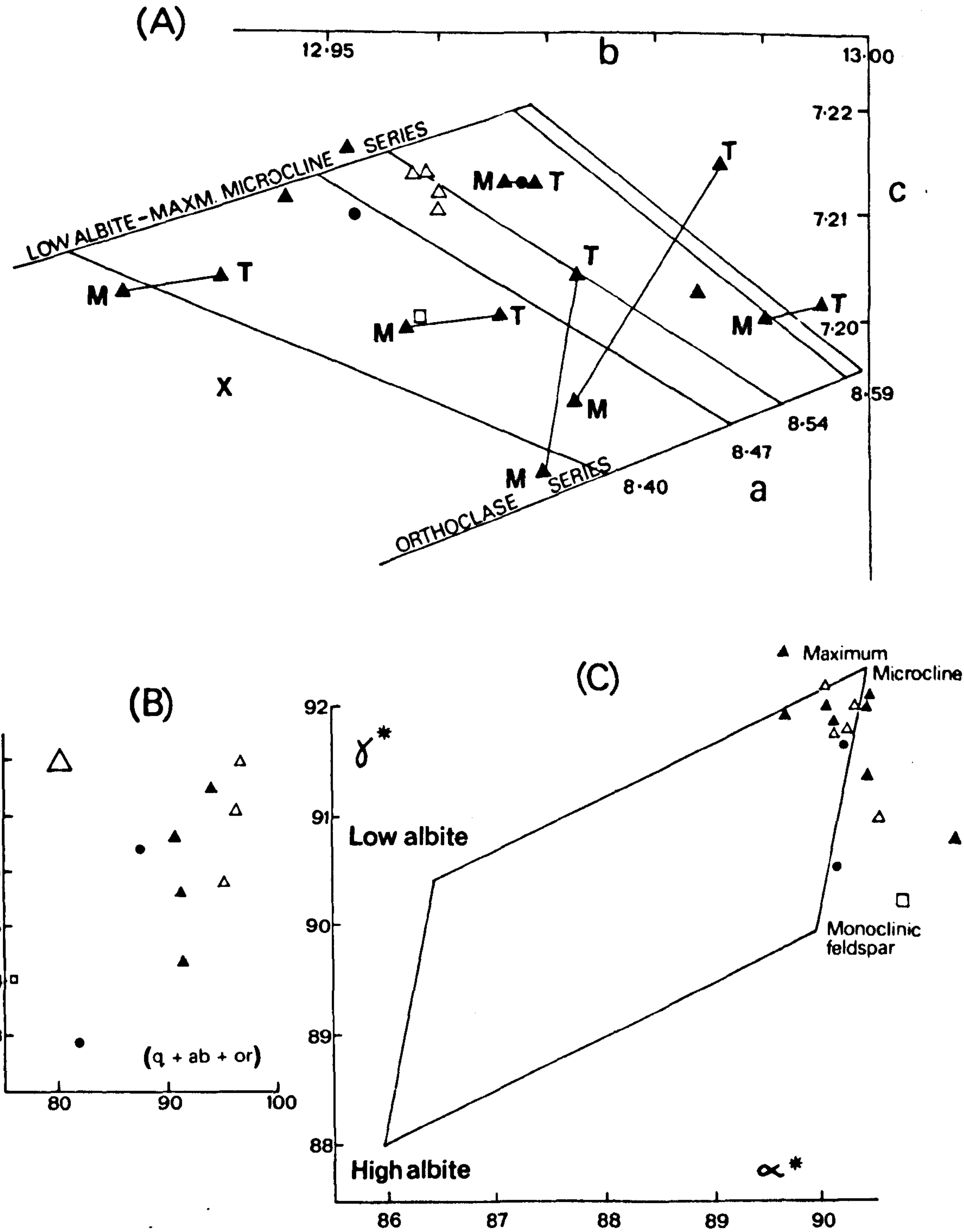


Fig. 6.4. Northern granites, K feldspars

A b-c plot key as figure 6.2 M- monoclinic T triclinic.

B Obliquity v. differentiation index.

C $\gamma^* - \alpha^*$ plots.

Stewart, 1968) with 'a' much larger than found in alkali exchange series feldspars with comparable 'b' and 'c' parameters.

Figure 6.4B shows that there is a reasonably strong correlation between obliquity and differentiation index (normative quartz + albite + orthoclase) throughout the various rock-types.

Discussion

The variation in the distribution of the structural states of the K-feldspars in the Northern granites may be explained in terms of primary variation as a result of the initial intrusion and cooling of the rocks. Earlier members in the series contain both orthoclase and microcline. The structural state of the microcline depends on the rate of the orthoclase-microcline transformation compared with the rate of cooling. In some areas the reaction was comparatively very sluggish and only a little intermediate microcline was formed, in others the reaction was comparatively more rapid and all the K-feldspar was transformed to near maximum microcline. The later members of the series, the Cap de la Hague granodiorite and particularly the Ecuty granite contain near maximum microcline with no trace of orthoclase. In the St. Germain granite the degree of equilibrium achieved in the distribution of the structural states of the K-feldspars is variable. In the Ecuty granite equilibrium was much more closely approached, with five separate samples collected from widely spaced localities all showing very similar structural states. Conditions in these rocks must have been particularly favourable for the orthoclase-microcline transformation. Sample 991 of Ecuty granite is from a fine grained dyke about 2 m wide (see plate 6.12) and this also contains only near maximum microcline despite the apparently rapid cooling of the dyke. However, sample 175 is from a gneissose raft included within the Ecuty granite and it contains intermediate microcline rather than maximum microcline.

This seems to support the hypothesis of Parsons and Boyd (1971) that the conditions at the time of initial crystallization may be an important control in determining the later form of the K-feldspar. The positive correlation between obliquity and differentiation index also supports this hypothesis (see figure 6.4B).

Chemistry of the Northern Granites

A number of samples were selected for analysis as being representative of the different phases of the Northern granites. The methods of analysis used for both major and trace elements are outlined in the Appendix.

Major Elements

The results of the major element analyses are given in Table 6.8. Each rock type established from field and petrographic criteria also shows distinctive chemical characteristics in the general range of concentration of most elements present in each type but particularly on their SiO_2, MgO, CaO, K_2O and P_2O_5 content.

That there is also a general range of variation throughout the series with variation in SiO_2 content may be demonstrated by the use of Niggli variation diagrams where each of the Niggli numbers is plotted against Niggli si (see figure 6.5). The usual trends of variation said to be associated with magmatic differentiation are obtained. However, the trends for al, c and k in particular show marked differences in slope for the first three members of the series compared with those for the last three members of the series. This change in slope corresponds with the point where hornblende ceases to be a mineral phase and K-feldspar begins to be important.

When the samples are plotted on an AFM triangular diagram (see figure 6.6A) they fall on a calc-alkaline trend which is elongated towards the alkaline apex showing extreme depletion in FeO and MgO

TABLE 6.8

CHEMICAL ANALYSES OF THE NORTHERN GRANITES

	Mela-dior-ite	Leuc-odior ite	La Becchue		Houffet		Cap de la Hague			
	91	101	457	465	407	188	9914	450	379*	456*
SiO_2	50.1	55.5	61.7	62.0	64.7	64.1	71.1	71.8	71.58	72.73
TiO_2	1.02	0.85	0.62	0.64	0.50	0.54	0.18	0.16	0.21	0.18
Al_2O_3	18.30	18.89	19.34	18.96	18.06	17.98	17.02	15.94	16.62	15.59
Fe_2O_3	2.25	1.89	1.90	1.29	1.08	1.39	0.34	0.38	0.15	0.35
FeO	7.64	5.90	2.41	3.01	2.50	2.29	1.46	1.58	2.0	1.89
MnO	0.17	0.14	0.06	0.08	0.06	0.06	0.02	0.03	0.03	0.03
MgO	4.90	2.65	1.76	1.92	1.34	1.52	0.89	0.52	1.15	1.07
CaO	8.87	6.48	5.02	4.06	3.34	2.65	0.41	2.32	0.62	0.46
Na_2O	3.13	3.34	5.00	4.80	4.80	4.90	5.28	4.67	5.71	4.86
K_2O	1.20	1.90	1.60	1.65	1.82	2.40	2.40	1.77	1.76	2.72
P_2O_5	0.33	0.34	0.24	0.24	0.19	0.19	0.07	0.05	0.09	0.08
H_2O^+	1.77	1.93	1.41	1.74	1.57	1.58	1.50	0.97	N.A.	N.A.
	99.62	99.81	101.06	100.39	99.96	99.60	100.67	100.19	99.92	99.96

	St. Germain granite						Ecuty granite			
	228	442	265	9915	378	167	991	993*	994*	995
SiO_2	74.6	74.6	74.0	74.4	75.1	78.2	76.5	75.82	75.64	76.7
TiO_2	0.24	0.17	0.24	0.21	0.14	0.02	0.05	0.05	0.05	0.04
Al_2O_3	14.45	14.77	14.16	14.34	13.46	11.56	12.32	12.32	12.40	12.40
Fe_2O_3	0.13	0.09	0.13	0.14	0.09	0.00	0.07	0.0	0.05	0.15
FeO	1.22	1.18	1.60	1.34	1.07	0.75	1.04	1.21	1.13	0.85
MnO	0.03	0.02	0.03	0.03	0.03	0.01	0.04	0.03	0.03	0.03
MgO	0.50	0.53	0.69	0.58	0.41	0.05	0.06	0.27	0.27	0.06
CaO	0.38	0.34	0.36	0.42	0.17	0.24	0.45	0.44	0.38	0.30
Na_2O	4.32	4.70	4.50	4.32	4.50	3.50	3.55	3.77	3.86	3.82
K_2O	3.50	3.29	3.25	3.80	3.55	4.60	4.90	5.85	5.94	4.77
P_2O_5	0.05	0.04	0.06	0.05	0.04	0.01	0.01	0.03	0.03	0.01
H_2O^+	1.02	0.84	1.14	0.95	0.73	0.49	0.47	N.A.	N.A.	0.51
	100.44	100.57	100.16	100.58	99.28	99.43	99.46	99.79	99.78	99.64

N.A. Not analysed. * Determined by X.R.F.

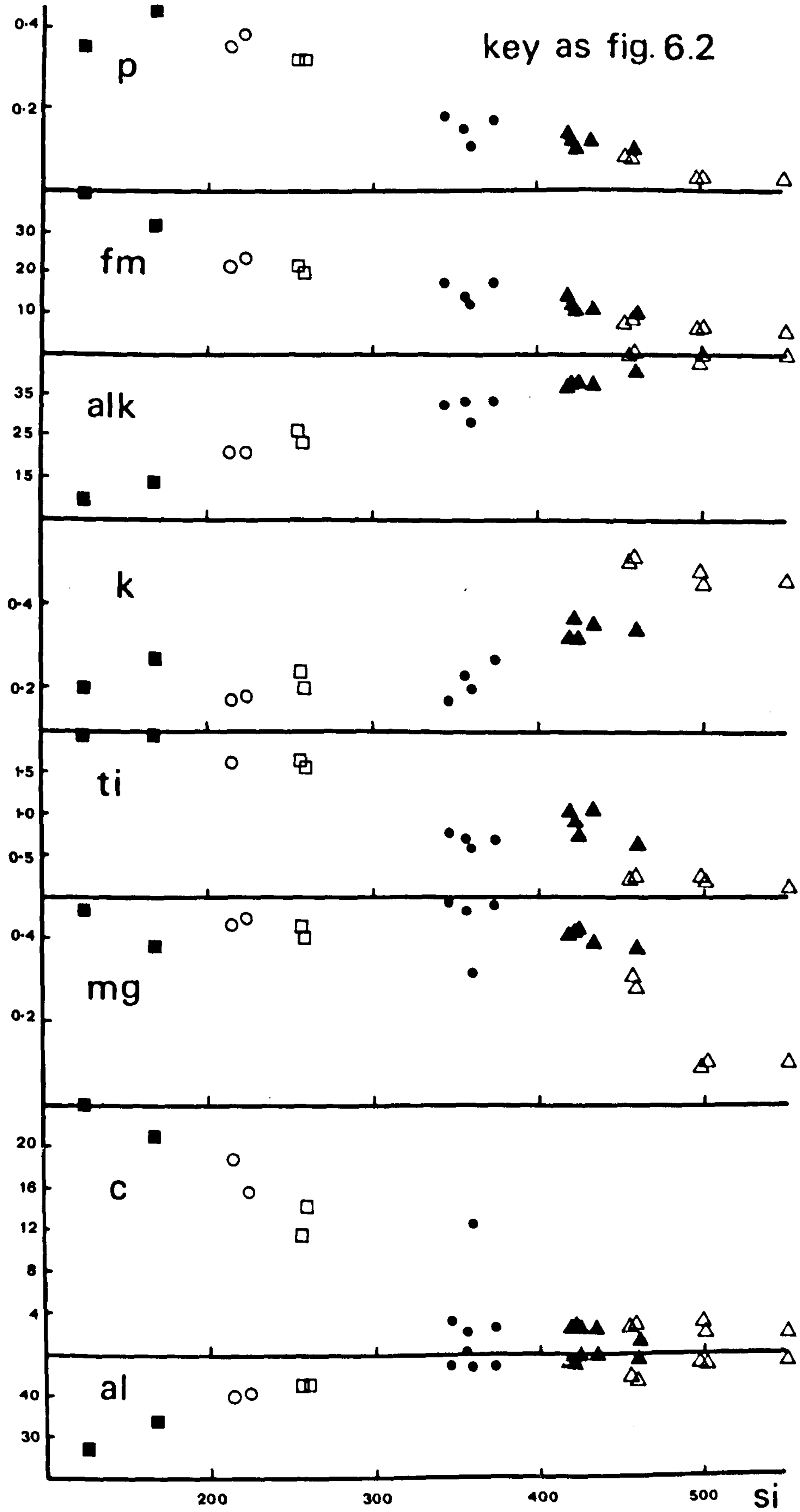


Fig. 6.5 Northern granites,
Niggli number variation diagrams.

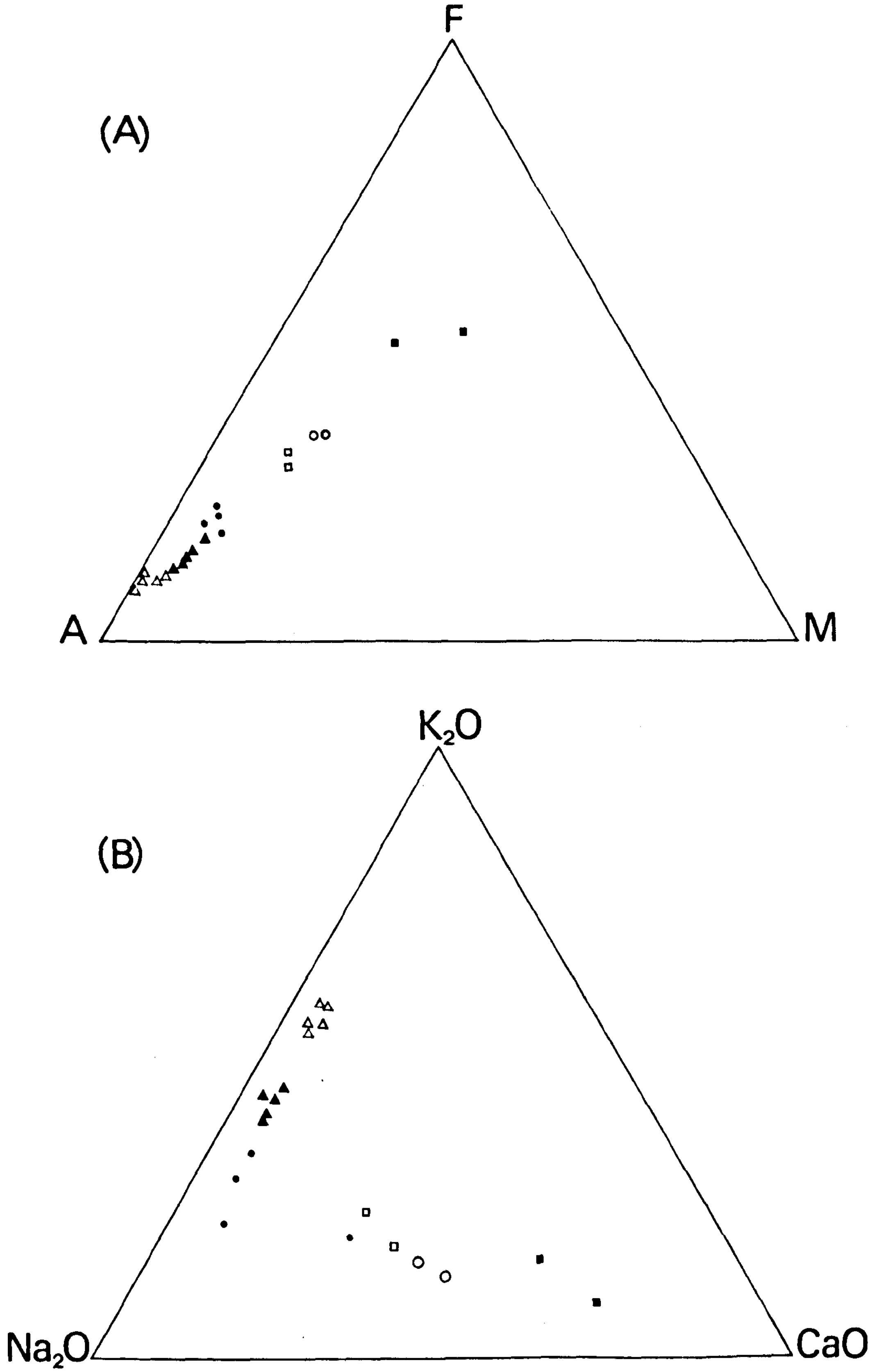


Fig.6.6 Northern granites
(A) AFM plot.
(B) Na_2O-K_2O-CaO plot.
KEY AS FIGURE 6.2.

relative to total alkalis ($K_2O + Na_2O$). The samples from the St. Germain granite and the Ecuty granite plot on this extended part of the trend.

On a triangular diagram of $Na_2O - K_2O - CaO$ (figure 6.6B) the samples form a trend which may be divided into two parts. The early members and the Cap de la Hague granodiorite plot on a fairly normal trend for a calc-alkaline series but perhaps with less relative K_2O than is often usual. The St. Germain granite and the Ecuty granite fall on a trend showing extreme relative depletion in CaO and relative enrichment in K_2O.

The order of the rock types on both these diagrams is agmatitic diorite, La Becchue quartz diorite, Houffet granodiorite, Cap de la Hague granodiorite, St. Germain granite and Ecuty granite, that is following the compositional series rather than the series corresponding to relative age based on field evidence. This compositional sequence is also found to apply for variation in Niggli si and most of the trace element variation trends.

Trace Elements

The results for the trace element analyses are given in table 6.9. The elements analysed all seem to be present in fairly normal amounts ranging around the values for an average granodiorite (Taylor, 1968).

Rubidium, thorium, uranium and to a lesser extent lead show little variation throughout the series but show a marked concentration in the Ecuty granite. Rubidium, thorium and uranium have been shown to exhibit preferential concentration in residual magmas (Taylor, 1965).

Lanthanum, cerium, neodymium and yttrium are all present in amounts showing little variation with position in the series.

Barium, strontium and zirconium initially increase with increasing Niggli si and then decrease (see figure 6.7). The change in their

TABLE 6.9

TRACE ELEMENT ANALYSES (IN PPM) OF THE NORTHERN GRANITES

	Meladiorite	Leucodiorite	La Becchue		Houffet	
	91	101	457	465	407	188
Rb	37	75	40	56	56	60
Ba	431	683	917	1109	912	1270
Pb	11	15	10	11	13	8.4
Sr	619	706	991	983	965	951
La	22	26	28	24	22	20
Ce	42	44	37	40	37	28
Nd	39	40	29	29	27	24
Y	22	22	6	6	8	4
Th	n.d.	n.d.	n.d.	n.d.	1.5	n.d.
U	n.d.	n.d.	n.d.	n.d.	n.d.	1
Zr	78	119	178	170	157	196

Cap de la Hague granodiorite

	9914	450	379	456
Rb	70	58	83	54
Ba	591	704	577	286
Pb	5.8	14	5.2	3.6
Sr	356	577	218	279
La	19	28	13	22
Ce	35	46	39	33
Nd	29	26	26	25
Y	2	9.6	0	4
Th	n.d.	1.2	2.1	n.d.
U	n.d.	n.d.	n.d.	n.d.
Zr	115	126	102	120

n.d.: not detected.

TABLE 6.9
(Continued)

TRACE ELEMENT ANALYSES (IN PPM) OF THE NORTHERN GRANITES

St. Germain Granite

	9915	378	9916	228	233	265	371	442
Rb	113	91	86	82	107	83	69	81
Ba	1216	1038	721	1284	1446	1314	925	1178
Pb	10	8	8	13	16	7.4	4.6	6.3
Sr	290	170	200	259	174	228	270	213
La	30	32	28	33	32	32	52	30
Ce	52	54	43	53	49	53	72	46
Nd	21	30	23	31	27	25	34	25
Y	3	14	4	12	1.4	0.2	2.7	2.1
Th	7.8	8.5	9.1	8.3	7.6	10	10	8.6
U	n.d.	n.d.	n.d.	2.1	1.5	n.d.	n.d.	2.8
Zr	101	85	89	93	79	125	151	91

Ecuty Granite

	991	993	994	995	167
Rb	266	242	228	258	203
Ba	59	208	182	109	85
Pb	17	17	15	15	13
Sr	19	52	40	28	25
La	15	41	29	16	12
Ce	30	63	51	34	21
Nd	20	27	28	24	24
Y	10	10	28	18	12
Th	40	33	33	39	36
U	10	6.3	5.2	9.3	6.1
Zr	83	91	93	88	64

n.d.: not detected.

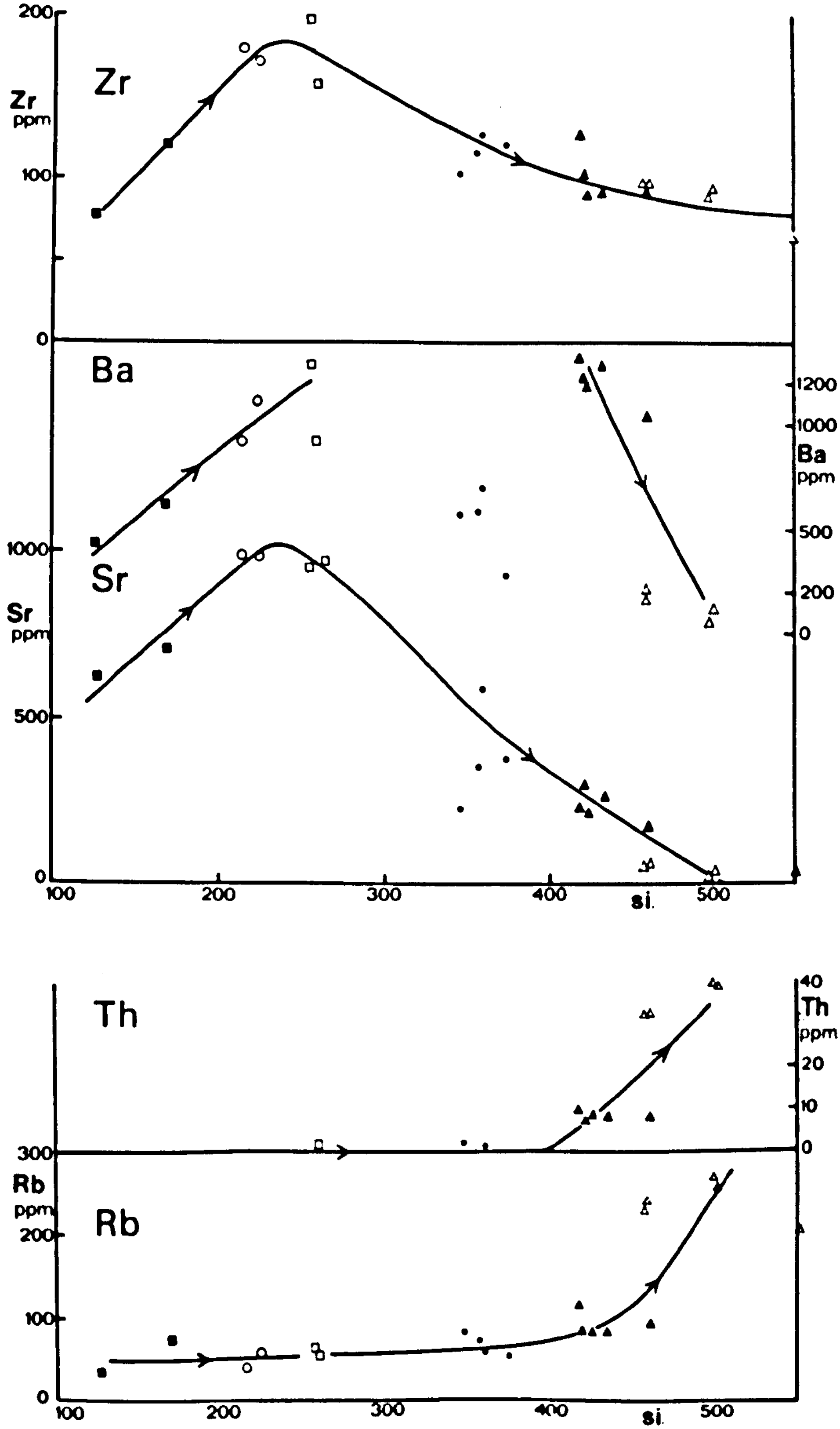


Fig. 6.7 Northern granites, trace elements v Niggli si.
key as figure 6.2.

behaviour takes place after the first three members of the series at the same point at which other changes have already been noted. Nockolds and Allen (1953) show that in a selection of calc-alkaline rock series there is a general increase in barium and strontium with differentiation but that in two series (E. Central Sierra Nevada lavas and Scottish Caledonian igneous rocks), which have more highly differentiated end products than the others studied, the final most differentiated members are depleted in barium and strontium. They also show a similar though less pronounced trend of variation for zirconium as that obtained for the Northern granitic series.

A plot of rubidium against strontium content for the Northern granites is shown in figure 6.8. This may be divided into two parts. In the early part of the series there is little variation in rubidium with increasing strontium content whilst in the later part of the series there is a marked increase in rubidium with decrease in strontium.

A plot of barium against strontium for the rocks of the series shows apparently complex variation (figure 6.8). Again, this may be resolved into an early series with barium and strontium increasing together and a later series with barium and strontium decreasing together, although the samples from the Cap de la Hague granodiorite do not fall on either part of the series.

A review of K-Rb fractionation trends (Shaw, 1968) shows that there are three probable trends for igneous rocks; that followed by oceanic tholeiites, a main trend and a pegmatitic-hydrothermal trend. The main trend for igneous rocks is linear on a log-log plot. Figure 6.8 shows the potassium and rubidium results for the Northern granitic rocks on a log-log plot. Superimposed on this are the probable limits for the main igneous K-Rb fractionation trend as summarised by Shaw. Most of the samples appear to follow the main igneous trend but

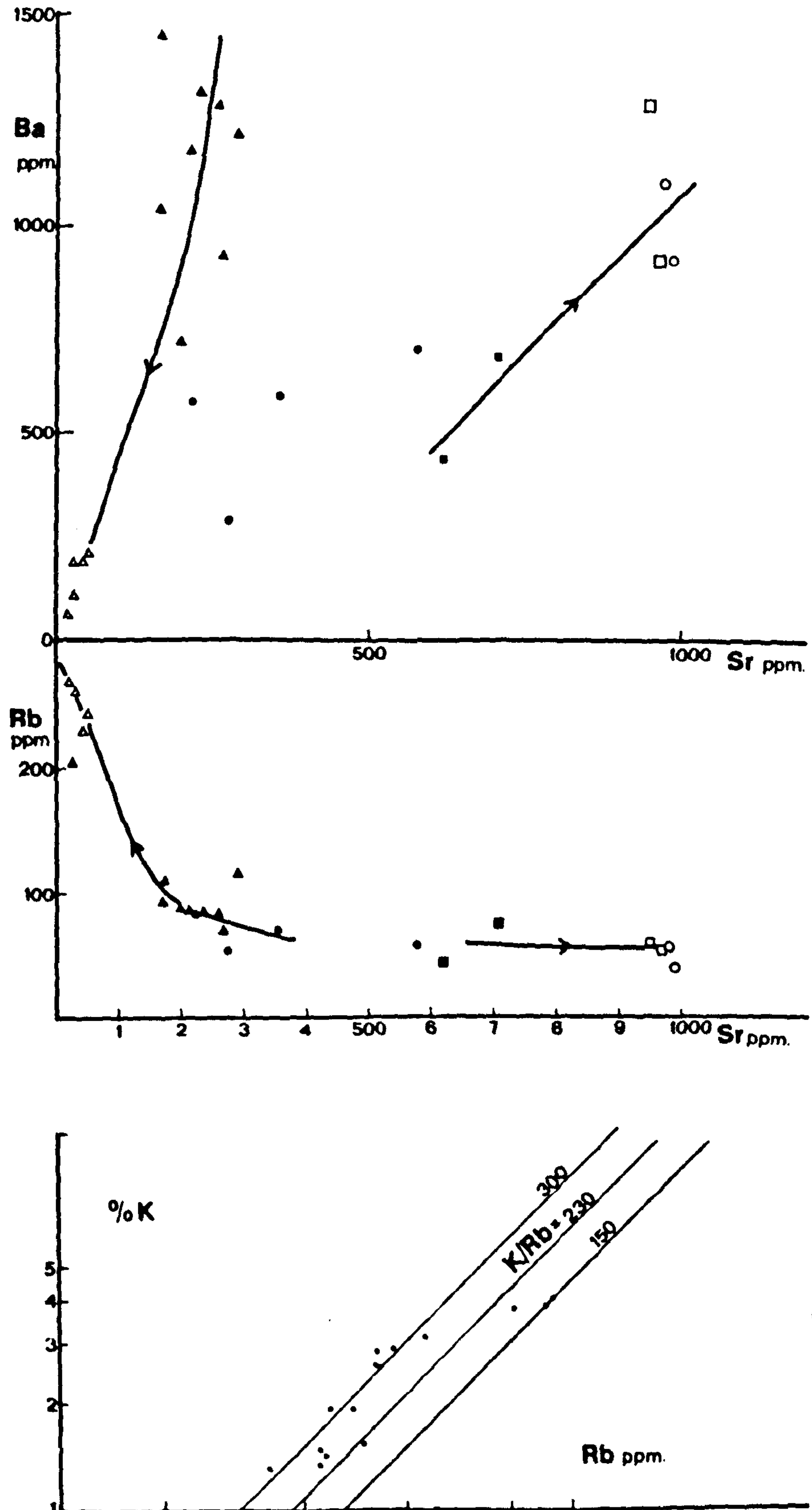


Fig. 6.8 Northern granites, trace element ratio plots – key as figure 6.2. except K/Rb plot.

at the top end of the plot the samples from the Ecuty granite fall markedly away from this trend. They have a lower K/Rb ratio and tend much more towards the trend expected for pegmatitic-hydrothermal rocks.

<u>Petrogenesis of the Northern Granites</u>

Their close association in the field, together with the regular mineralogical and chemical variations, make it most likely that all the different rock types constituting the Northern granites belong to a single magma series. The marked changes in the chemical variation plots reflect the change from hornblende and plagioclase to plagioclase, K-feldspar and quartz as the main crystallising phases. The later members of the series, particularly the Ecuty granite, show all the characteristic features of strong fractionation. When the analyses are plotted on the Ab - An - Or and Ab - Q - Or faces of the system Ab - An - Q - Or those from the St. Germain granite and the Ecuty granite plot close to the projection of the univariant line (see figure 6.9), providing additional evidence that they are late stage fractions of the magma.

The rocks belonging to a magma series are usually intruded in strict sequence from the more basic to the more acid members although this is not always the case. Various hypotheses may be offered to account for the difference between the intrusive and compositional sequence for the Northern granites. For example, different vertical levels of a compositionally zoned magma chamber could have been tapped at different times. There could have been two levels of fractionation interacting, one at depth and a second at a shallow level. Assimilation of a more basic early phase could have given rise to a later phase more basic than expected. However, the nature of the evidence does not allow any firm conclusions to be drawn regarding the particular mechanism active in this case.

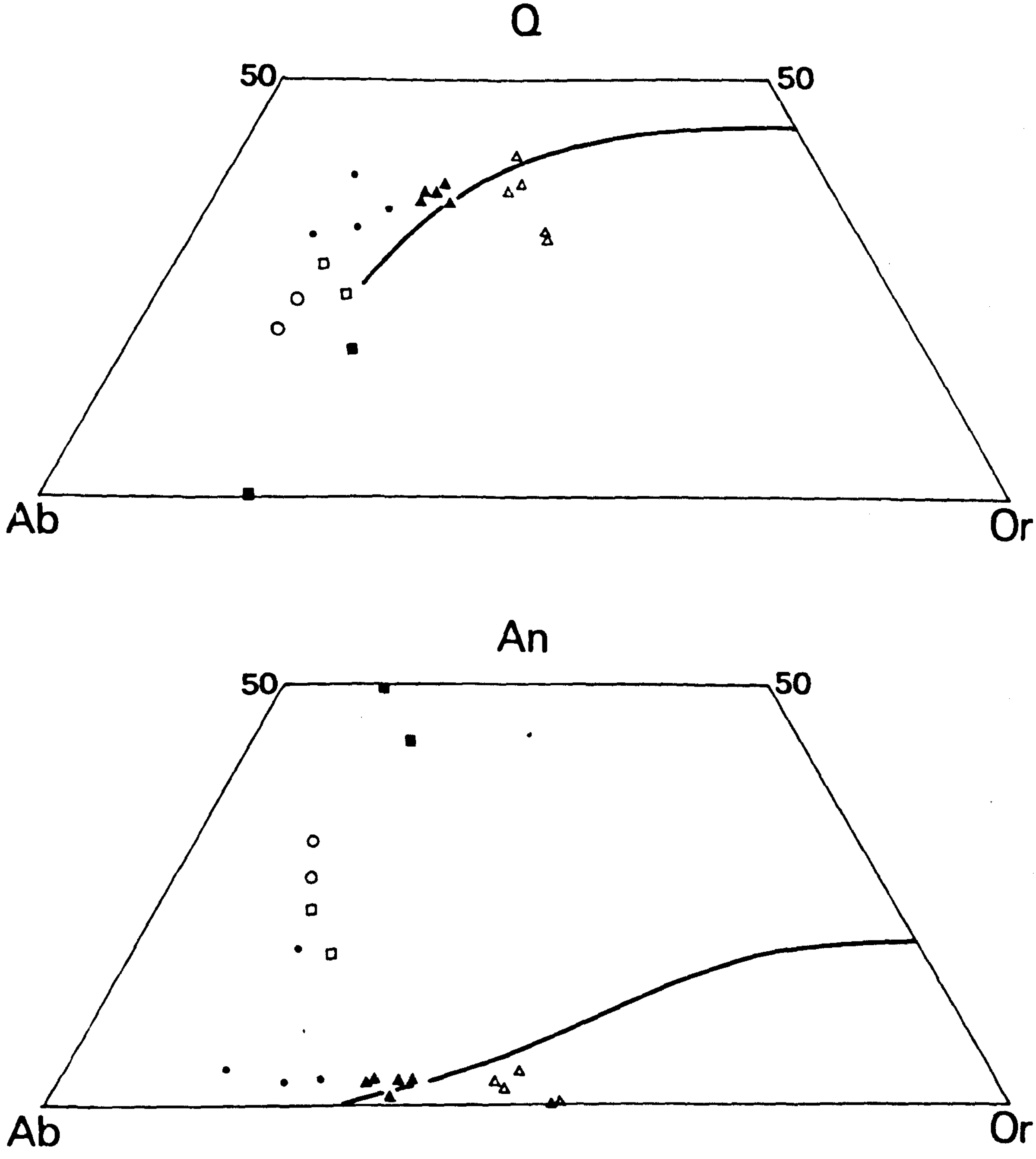
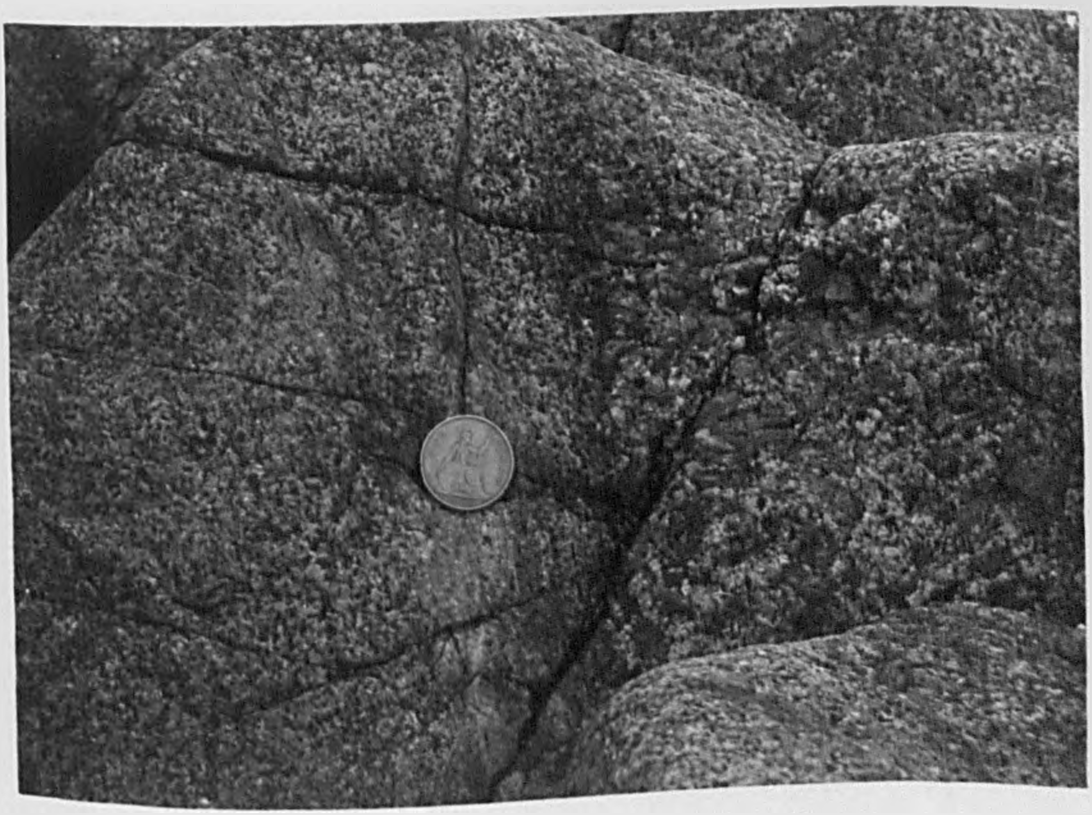


Fig.6.9. Northern granites, Ab-Q-Or and Ab-An-Or plots with projection of univariant line.

It is considered that there may have been some reaction between phases, particularly the earlier members of the series. The meladiorite and leucodiorite show an agmatitic relationship to each other, rafts of the agmatite are enclosed in the Houffet granodiorite which in turn forms rafts in the La Becchue quartz diorite. In addition, there are many rafts of a coarse granite, probably the original country rock, included in the earlier members of the series. However, it has not been possible to estimate the amount of any assimilation or its effects. Certainly the presence in certain areas of the abundant large xenoliths of various types suggests that the present level of erosion may be close to the original roof of the intrusions and that they were emplaced by a mechanism of active stoping.

6.1 Dark green inclusions in St. Martin monzonite, Havre de Plainvic.

6.2 Contact between megacrystic and non megacrystic varieties of St. Martin monzonite, Havre de Plainvic.



6.3 Agmatitic diorite, les Roches du Houffet.

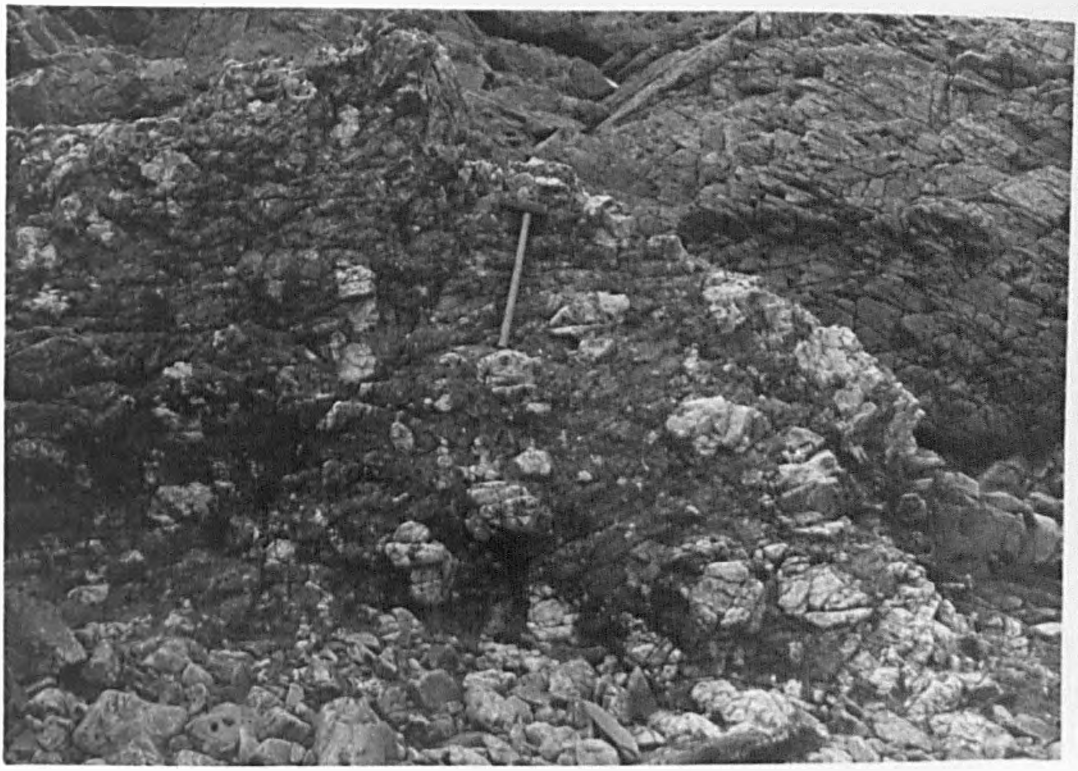
6.4 Block of agmatitic diorite in Houffet granodiorite, les Roches du Houffet.

6.5 Close up of texture of La Becchue quartz diorite.

6.6 Cap de la Hague granodiorite vein cutting Sary granodiorite.

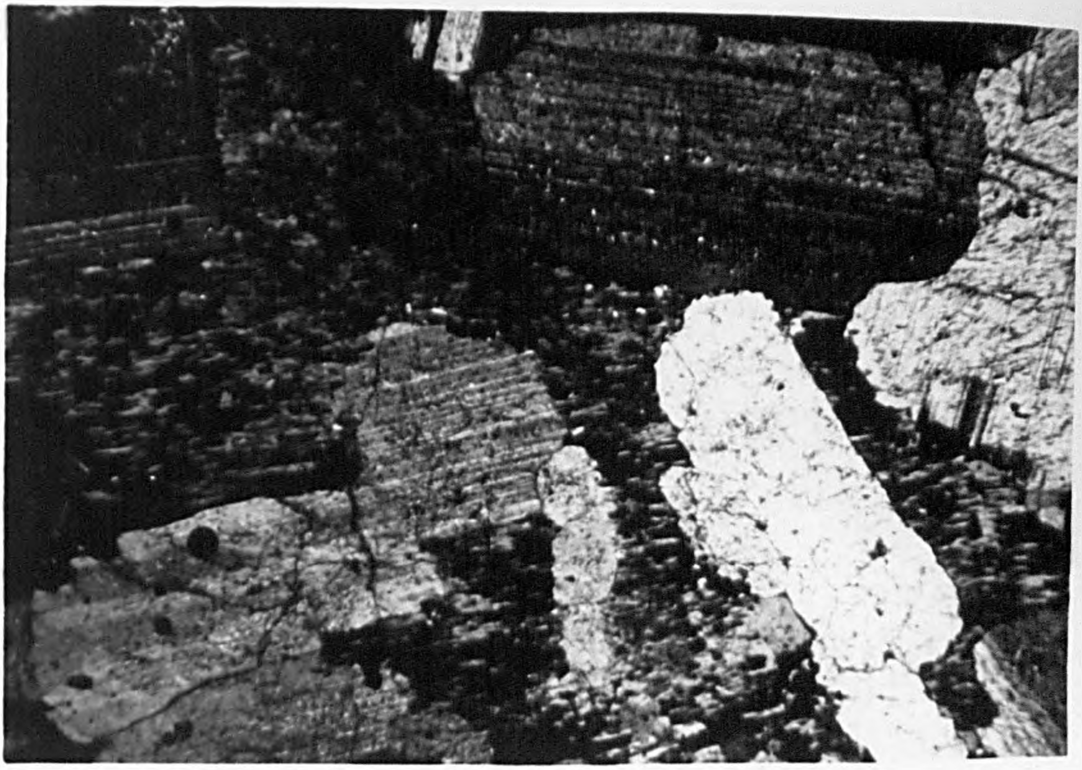
6.7 Pegmatite, Ecuty granite, Baie d'Ecuty.

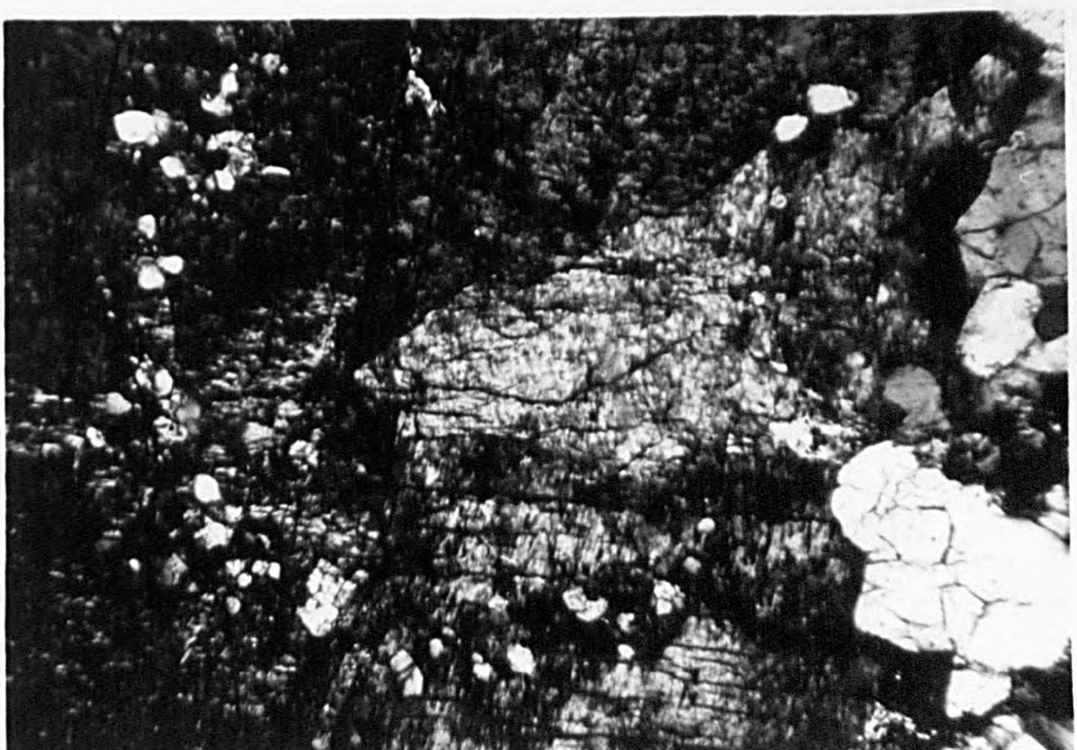
6.8 Zone of cataclastic deformation in
Cap de la Hague granodiorite, Cap de la Hague.



6.9 Growth of albite at grain boundaries, St. Germain granite, crossed polars, X11.2.

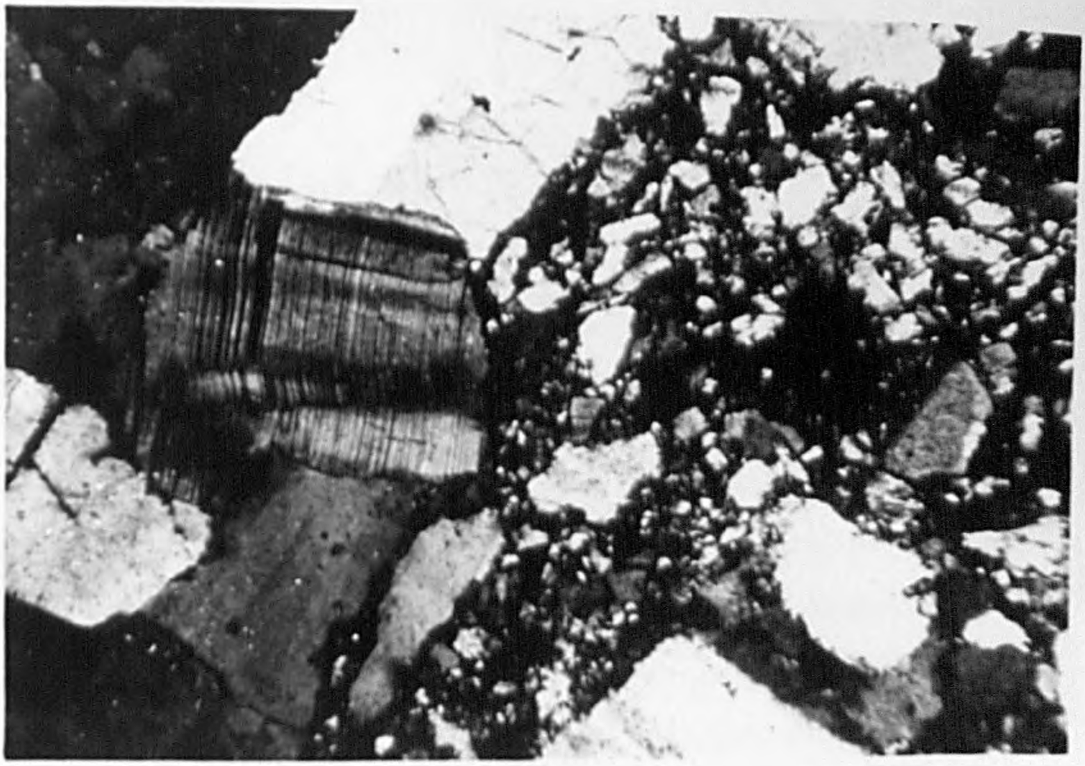
6.10 Replacement of K-feldspar by albite, St. Germain granite, crossed polars, X11.2.

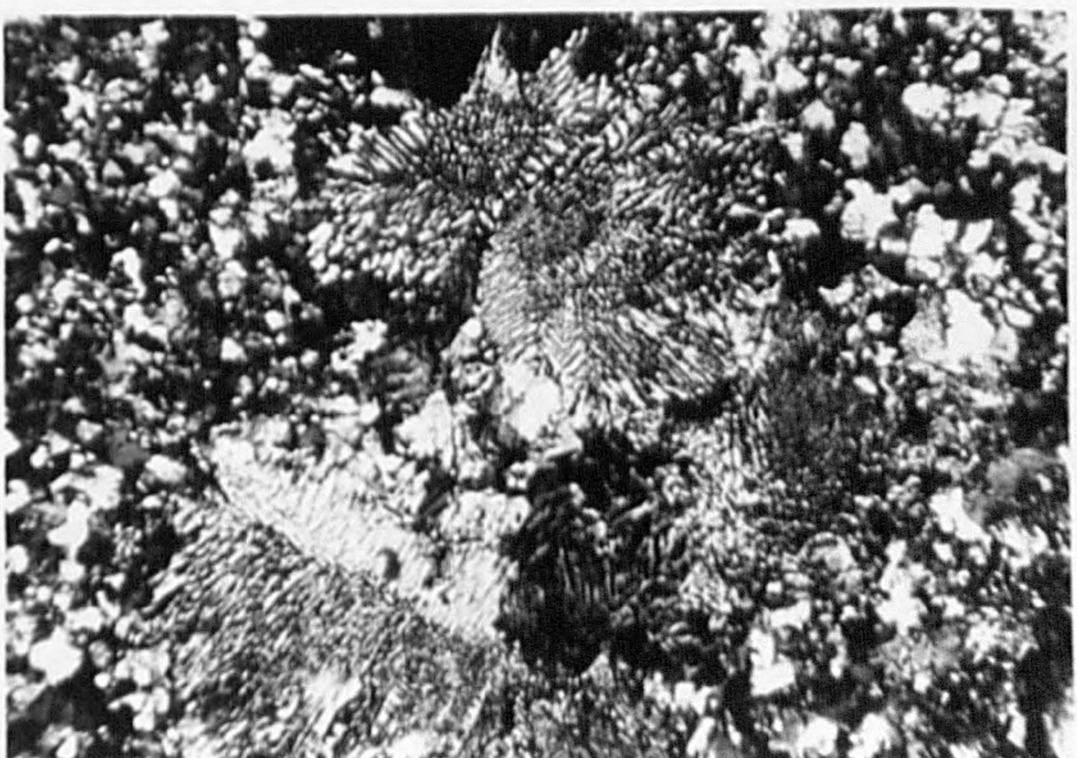




6.11 Cataclastic deformation in St. Germain granite, crossed polars X11.2.

6.12 Fine grained granophyric intergrowth in dyke from Ecuty granite. Crossed polars X32.





CHAPTER 7

NOTES ON THE LOWER PALAEOZOIC ROCKS OF LA HAGUE

A large area of La Hague is covered by Lower Palaeozoic sediments (see figure 2.1). However, it is not intended to deal exhaustively with the geology of these rocks. Coates (1965) has already studied the geology of the Jobourg and Siouville synclines, Manche in his Ph.D. thesis. This chapter merely gives a few brief comments on the nature of the sediments and their deformation so that the Precambrian geology of La Hague may be set more fully into perspective.

The Nature of the Lower Palaeozoic Sediments

The Cambrian sediments of La Hague are unfossiliferous conglomerates, arkoses, sandstones and shales. They have been assigned a Cambrian age because they are considered to underlie the Grès Armoricain (Arenig), (see Graindor, 1960b). It is not possible to assign these sediments to a stratigraphic level within the Cambrian.

Inland quite good exposures of the Cambrian rocks are found on hillsides and in quarries but they are not sufficiently continuous to be able to construct a succession. They are well exposed on three sections of coast; north of Baie d'Ecalgrain at Pointe du Houpret, near Herquemoulin at Le Houguet and east of Omonville-la-Rogue at Pointe d'Etimbert and it is from these three sections (see table 7.1) that a generalised succession may be drawn up. This may be divided into five main divisions starting from the oldest rocks and working up the succession.

1. Massive green or red grits with abundant quartz clasts up to 0.5 cm in size and larger pebbles of quartz, red shale and granite in lenses. May contain many K-feldspar fragments.

Pointe d'Etimbert Section	Pointe du Houpret Section	Le Houguet Section
		Fine grained, cross-bedded green-brown sandstone units 0.1-0.2 m.
	Dirty grey-green medium to fine grained irregular bedded sandstone with very fine impersistent black shaley bands and lenses.	Fine grained blue-grey laminated shale. Units 3 m thick. Occasional finely laminated mudstones with disrupted bedding occur in sandstone.
	Fine grained yellow, cross-bedded sandstone, 0.2-0.4 m thick units interbedded with thinner, green or brown sandstone with parallel laminations.	Fine grained yellow-green sandstone with abundant cross-bedding, Units 0.2-0.3 m. Dark olive-green sandstones, fine to medium grained, cross-bedded. Units 0.1-0.2 m.
Purple, fine grained cross-bedded sandstone interbedded with green cleaved shales.	Medium grained cross-bedded sandstone, interbedded with fine grained green fissile sandstone. Units 0.2-1 m.	Alternating fine grained, cross-bedded sandstones and shaley laminated soft yellow-green units.
Red, coarse grained arkoses. -?- Units 2-3 m.	Red, coarse grained cross-bedded -?- arkoses with K-feldspar and quartz clasts. Units 1-2 m thick.	Coarse grained yellow arkoses.
Grey-brown, medium to coarse grained grits. Massive, Bedding rarely seen.	Unconformity.	Fault.
Pale coarse grained grit. Some graded bedding and cross-bedding.		
Massive green grits with abundant quartz clasts, larger pebbles in lenses include: quartz, red shale and rare granite. Sometimes contains abundant K-feldspar fragments. Unconformity.		

Tentative correlation between sections shown: - ? -

TABLE 7.1

SUCCESSIONS WITHIN THE CAMBRIAN OF LA HAGUE

2. Pale coarse sandstones with some grading and cross-bedding and grey-brown medium to coarse grained massive sandstones.
3. Red coarse grained cross-bedded arkoses with units 2-3 m thick and lenses of conglomerate.
4. Red medium to fine grained cross-bedded sandstone units 0.5-1 m thick and interbedded thinner units of fine grained green or purple cleaved shales.
5. Grey-green medium to fine grained cross-bedded sandstone units 0.1-0.2 m thick with thin impersistent shaley bands which increase in thickness up the succession.

This sequence may be interpreted as a typical fluviatile and shallow water succession.

The Alderney sandstone has been correlated with the Cambrian of La Hague (e.g. Hill, 1889; Bigot, 1900) and the generalised succession for La Hague does bear a remarkable similarity to that given for the Alderney sandstone by Sutton and Watson (1970), although the highest division recognised in La Hague appears to be missing on Alderney. Sutton and Watson (1970) have attributed all these sediments to being the products of typical post-tectonic molasse type sedimentation.

Coates (1965) has given the most complete description of the Ordovician rocks of La Hague. The Grès Armoricain is well exposed at Herquemoulin and consists of quartzites and micaceous white sandstones, which towards the top of the succession are interbedded with thin shale horizons. The trace fossil Cruziana may be found at this locality. The Middle Ordovician occurs at Herqueville and at Chateau de Beaumont. A quartzite group is succeeded by bioturbated shales and a homogeneous blue-black shale which is frequently very fossiliferous (schistes à Calymene). The Upper Ordovician is well exposed in the Baie d'Ecalgrain and consists of quartzites, sandstones, dark shales and siltstones. The shales contain a variety of fossils including brachiopods, trilobites and fragments of crinoids, gasteropods, corals etc. (complete faunal lists are given by Coates, 1965). The lithology, sedimentary structures and fauna suggest a shallow-water shelf environment for the whole of the Ordovician.

Relationship of the Lower Palaeozoic Rocks to the Underlying Rocks

The presence of Cambrian sediments resting on other rocks allowed the early workers (e.g. Bigot, 1900) to assume a Precambrian age for these rocks. Jérémine (1930) gave a list of the main localities where it is possible to observe this relationship directly. This list is given below together with the nature of the underlying rocks.

1.	Pointe d'Etimbert	Gneisses of the Omonville area.
2.	Quarry, Omonville-la-Rogue	" " "
3.	South of Diotret	Sary granodiorite
4.	South of Greniquet	" "
5.	Le Houguet	Faulted against Moulinet dioritic gneiss.
6.	Old quarry north of Beaumont-Hague.	St. Martin monzonite.
7.	La Brasserie, near Digulleville	" " "
8.	Laye	Cap de la Hague granodiorite.

To illustrate the relationships more fully the nature of some of these contacts and their associated structures will be described.

At Pointe d'Etimbert the Cambrian sediments may be seen in direct contact with the gneisses of the Omonville area (see plate 7.1 and end map 5).

The contact strikes 22°E of N and dips 34°E. The sediments at the contact are coarse grained grits with abundant small quartz clasts and lenses containing larger pebbles of quartz, red shales and sometimes granite. The units are fairly massive and near the contact strike 58°E of N and dip 66°SE. In other words they cannot have been deposited directly on the present surface of the contact. The sediments are deformed as may be seen from the shape of the pebbles and the development of a poor cleavage (see plate 7.2). This cleavage strikes 22°E of N and dips 37°E. That is, virtually parallel to the contact (see end map 5). The underlying gneisses have a shear foliation developed in them which increases in intensity as the contact is approached. About 100 m away from the contact it is nearly parallel to the foliation in the gneisses and appears to be partly controlled by the attitude of this foliation. Closer than 50 m to the contact the shear foliation becomes more obvious and more closely spaced. It strikes 13°E of N and is inclined 50°E. That is slightly steeper than the attitude of the contact.

Traversing south along the coast the grits may be seen to be folded. The folds are asymmetric, anticlines having a long northern limb dipping south at a moderate angle and a very much shorter southern limb dipping south at a steep angle. The folds plunge at 20° towards 60°E of N. These observations suggest a sense of movement of the grits towards approximately SSE. About 100 m south of Pointe d'Etimbert very sheared gneisses are again exposed in a small 'window' in the grits. The presence of the contact here could mean that, although the covering grits were folded, the contact plane itself was not. The succession is repeated south of this point and strongly elongated pebble conglomerates occur rich in K-feldspar fragments. The elongation of the pebbles trends 60°E of N.

The sediments young towards the south as indicated by cross-bedding evidence. The last 200 m of the section are much more obviously folded than the preceding rocks and tight folds, varying from upright to southwards overturned, are seen. The lithology is alternating beds of sandstone and shale. The more competent sandstone units are often dislocated by the folding and an almost vertical cleavage striking 60°E of N is developed in the shales. The fold axes plunge gently in a similar direction. The folding becomes more intense, contorted and broken, and the sediments may again be seen to rest on sheared gneisses on the north side of the bay north of Baie de la Quervière. Thus, the oldest and youngest beds in the section rest directly on the underlying gneisses. The valley behind this bay is the line of a large scale fault (see end map 1) and contains thrust slices of what may be Grès Armoricain.

All the features described present a strong case for a comparatively thin cover of Cambrian sediments having been deformed and thrust in an approximate south-south-east direction over a series of gneisses.

The old quarry north of Beaumont-Hague, where Jérémine (1930) recorded a contact between the Cambrian and the St. Martin monzonite, is now disused and partly filled in, so that the contact is no longer visible. It is possible to observe, however, that the attitude of the bedding in the Cambrian sediments is very nearly vertical. All along the edge of the Cambrian outcrop, both east and west of Beaumont-Hague, the bedding in the Cambrian sediments is invariably steep within what must be very short distances of the contact (see end map 1). The only place where an actual contact can be observed was in a cutting for a farm track close to La Brasserie south-west of Digulleville. Extremely weathered St. Martin monzonite occurs beneath the contact and the plane of the contact strikes 22°E of N and dips 20°E. Immediately above the contact there is a zone 10 m wide of very broken and weathered Cambrian sandstones. Beyond this zone a shaley band in the sandstones strikes 72°E of N and dips 70°S. This association of steeply dipping sediments above a fairly shallowly inclined plane of contact with the underlying rocks cannot be an original sedimentary junction and seems more likely to have resulted from thrusting of the Cambrian sediments.

The Cambrian sediments exposed along the west coast stretch from near La Roche to Pointe du Houpret (see end map 4). The rocks young towards the south. Jérémine (1930) interpreted the most northerly contact, said to be near Diotret, as Cambrian sandstones deposited on a surface produced by weathering during Precambrian times, the whole unconformity having been subsequently tilted to its present attitude. The sandstones consist of coarse red arkoses with conglomeratic lenses and interbedded medium grained sandstones. They strike about 60°E of N and dip about 60°S. The general surface of the contact has a similar orientation which may give it the appearances of an original sedimentary surface. However, in detail it is irregular and may locally make a high angle with the bedding (see plate 7.3). The underlying rock is the Sary granodiorite and close to the contact it is very altered. At least some of this alteration is the result of shearing of the granodiorite. Traversing southwards over the Cambrian sediments a succession is crossed which is listed in table 7.1, under the heading, 'Pointe du Houpret section'. On the north side of Baie de Sary the sandstones become progressively more deformed and continuous bedding is lost. Beds become broken, streaked out and intensely veined by quartz. Large quartz veins contain fragments of rock within them. Small folds plunge at angles of about 40° towards the east. This zone of contorted beds rests directly on cataclased Cap de la Hague granodiorite.

On the south side of the bay, Sary granodiorite is again overlain by Cambrian sediments. This contact is very similar to the previous one and a similar series of red arkoses overlies the contact. However, the succeeding sequence has been complicated by faulting and does not match up with the first succession, which was the most complete one recorded for the whole section. On the north side of Pointe du Houpret, in an area about 100 m wide, thin medium to fine grained pink sandstones, alternating with green fine grained sandstones have been intensely folded and broken up into a series of disconnected slices (see plate 7.4). The folds plunge towards the east at angles around 45° and the zone of contorted beds rests directly on steeply dipping red arkoses.

The Pointe du Houpret is mainly composed of units 2-3 m thick of coarse grained red arkoses. On the south side of the headland these have been thrust over finer grained yellow sandstones which have been deformed into a series of folds plunging east at angles around 50°. Further south, in Baie d'Ecalgrain, the red arkoses have been thrust over Ordovician sediments. This takes the form of several thrusts (see end map 4). First, the red arkoses have been thrust over a zone of broken red arkoses which in turn has been thrust over a zone of contorted Ordovician sandstones and shales containing a series of small folds plunging east at less than 10°.

The whole section of Cambrian rocks from La Roche to Pointe du Houpret appears to have suffered thrusting with a sense of movement from north to south. This has given rise to repetition of the Cambrian succession and to the thrusting of Cambrian over Upper Ordovician rocks to the north end of the Baie d'Ecalgrain. The zones of strongly contorted rocks are restricted in extent and appear to be confined to areas associated with the leading edge of a thrust block. This situation is also found in the Pointe d'Etimbert section. It may also be controlled to some extent by lithological variations, because the thicker units of coarse grained red arkoses are rarely disrupted to the extent of the thinner units of alternating sandstone and shale, which are often found in the zones of contorted rocks.

One final point regarding the Pointe du Houpret section should be mentioned. Graindor (1960b) suggested that in the Baie de Sary a granite younger than the Auderville granite had metamorphosed the Cambrian sediments and partly replaced them indicating that it must be post-Cambrian in age. He called this granite the Calenfrier granite. As shown in Chapter 6 the Auderville granite of earlier authors can be subdivided into several different intrusive phases. Graindor claimed that his Calenfrier granite was younger than the Auderville granite because veins of it cut the Auderville granite. What he saw was Cap de la Hague granodiorite cutting Sary granodiorite. No evidence of contact metamorphism was found in the Cambrian sandstones, although they have been deformed and recrystallized during the thrusting. It was not found possible to map out Graindor's outline for his Calenfrier granite, or to identify it as a recognisably different rock type. For all these reasons it is considered that the existence of the Calenfrier granite has not been established, let alone any firm evidence for its proposed post-Cambrian age.

The Upper Ordovician sediments of the Baie d'Ecalgrain have been folded into an asymmetric syncline slightly overturned towards the south. The fold axis trends nearly E-W and plunges very gently to the east. The beds on the northern limb dip at around 60°N and yet, from the evidence of ripple marks, cross-bedding and bottom structures, young to the south. The beds on the southern limb dip at about $45^{\circ}N$. The sequence of beds on each limb is not an exact repetition and it is possible that the northern limb has been affected by thrusting. Inland, to the east, the syncline disappears under thrust sheets of Grès Armoricain and Cambrian sediments.

Middle Ordovician beds are seen in the deep valley near Chateau de Beaumont where they form an inlier surrounded by Cambrian sediments. To the east of Herquemoulin, Ordovician rocks have been folded into a series of overturned folds with one fairly flat lying limb and the other steeply dipping and overturned (see plate 7.6). The fold axes of these folds trend south-east and plunge at about $20^{\circ}SE$. The sense of transport is from north-east to south-west. The attitude of these folds may be a local variation, as the main Siouville syncline further south-east trends west-east and plunges gently east.

Coates (1961) was of the opinion that both the folding at Baie d'Ecalgrain and the thrusting of Cambrian over Ordovician rocks were the result of a single continuing phase of deformation. However, Graindor (1961) stated that for the northern Cotentin region the synclines were produced by the Bretonnic phase of the Hercynian orogeny and the thrusting by the Sudètan phase. It has not proved possible to reach any firm conclusions on these distinctions from the limited area studied in La Hague.

Discussion

From the preceding descriptions it seems likely that most of the Cambrian sediments in La Hague are no longer resting on their original surface of deposition. This is the complete reverse of the conclusion reached by Jérémine (1930), although in an earlier work (Bigot and Jérémine, 1923) it was concluded that all the contacts were tectonic. If most of the Cambrian rocks have been moved relative to the rocks which now underlie them then these are not necessarily Precambrian in age as was assumed by the early workers. Detailed examination of the granitic pebbles in the Cambrian conglomerates does suggest that they could be matched in the granitic rocks of La Hague and the abundant K-feldspar fragments in some horizons could have originated from the St. Martin monzonite. It is therefore suggested that the Cambrian sediments were derived fairly locally and have not been tectonically transported far.

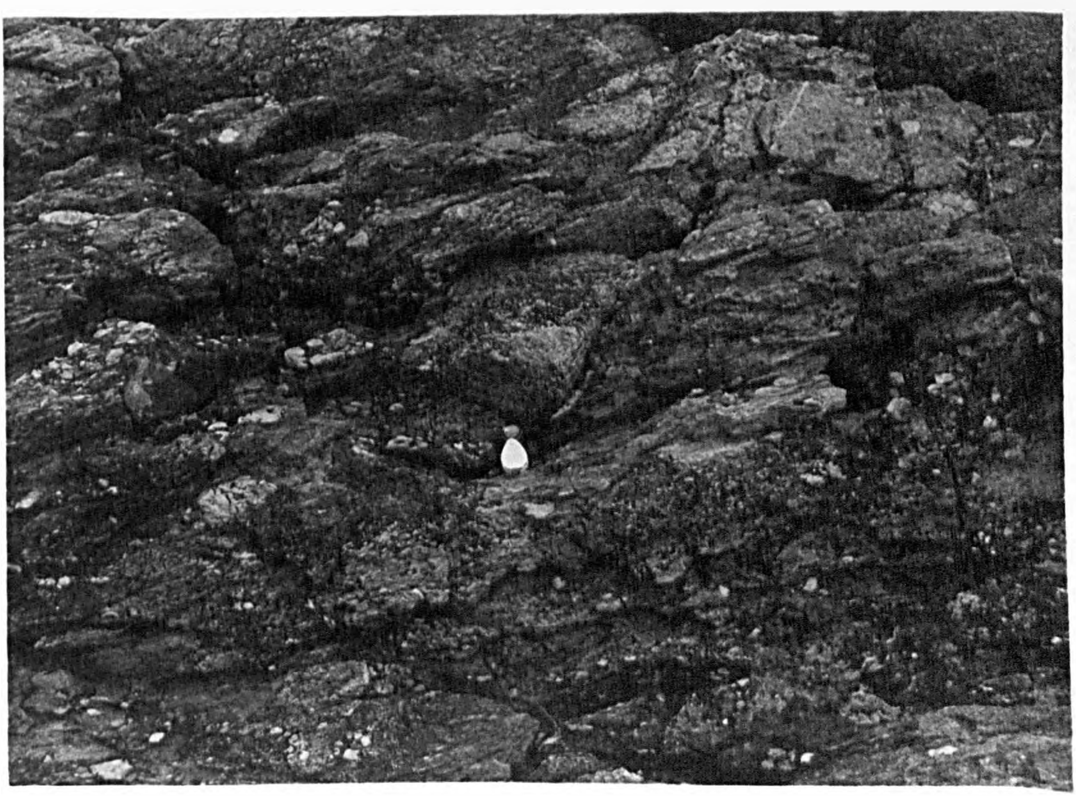
Previous workers (e.g. Graindor, 1960b, 1961; Coates, 1961) had recognised thrusts affecting the Cambrian in La Hague. Graindor emphasised the importance of thrusting in the north of the Cotentin and, in particular, gave as examples detailed accounts of the thrusts affecting the Grès Armoricain near Cherbourg. The new descriptions given in this chapter complement and reinforce Graindor's arguments.

Although the older rocks have often been sheared and suffered cataclastic deformation close to the contacts with the Lower Palaeozoic rocks it is difficult to assign any other affects in the older rocks categorically to this post-Cambrian tectonism. As already mentioned, it may have contributed to the present configuration of the contact at Baie de la Quervière and it is probably responsible for some of the faults affecting the older rocks. Renewed movements in the schists at Landemer would seem to have been likely but have not been established.

The direction of movement established for the thrusting in La Hague is from north to south. Graindor (1960b) has shown that this direction generally applies throughout a large area of the north of the Cotentin. Robardet (1970) demonstrated that for the central part of the northern border of the "Zone Bocaine" in Normandy similar thrust movements from north to south are common. All these observations contribute towards an indication of the regional importance of this type of movement.

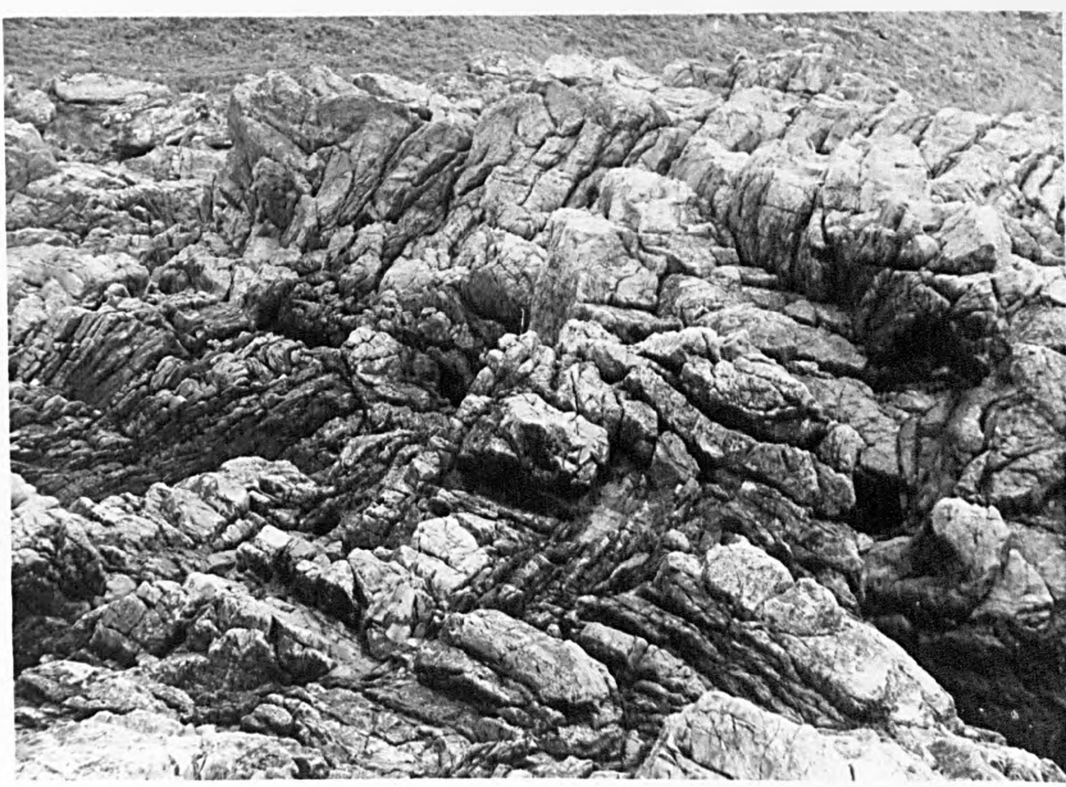
7.1 Cambrian unconformity with shearing in underlying gneiss, Pointe d'Etimbert.

7.2 Deformation in coarse Cambrian conglomerate, Pointe d'Etimbert.



7.3 Irregular contact between Cambrian sediments (bedding parallel to compass) and Sary granodiorite, Greniquet.

7.4 Contorted Cambrian sediments, Pointe du Houpret.



7.5 Accommodation structure in Ordovician sediments, Herquemoulin.

7.6 Recumbent fold in Ordovician sediments, Herquemoulin.

CHAPTER 8

GEOCHRONOLOGY

The published work on the geochronology of the northern part of the Armorican Massif is principally the result of the efforts of Leutwein and his co-workers at Nancy and of Adams at Oxford and more recently of Vidal at Rennes.

Several different techniques have been used to obtain the published results and it is important to consider the relevance of the results in the light of the limitations and assumptions of the particular methods used. Therefore a brief outline of each of the methods concerned is given first.

The K/Ar Method

Naturally occurring unstable ^{40}K decays by β-decay to ^{40}Ca and by electron capture to ^{40}Ar. The age determination method utilises the $^{40}K \rightarrow {}^{40}Ar$ part of the decay scheme. It assumes λe and $\lambda \beta$, the decay constants for each branch of the decay are known and have remained constant throughout geological time. It also assumes that the proportion of ^{40}K making up the total potassium content in different materials at present is known and is essentially constant. In the simple case, the most important assumptions are that there has been no gain or loss of ^{40}K and ^{40}Ar other than by radioactive decay.

Different potassium bearing minerals from whole rocks show different abilities to retain radiogenic argon. Whilst micas and amphiboles in undisturbed rocks show good argon retentivities with time, K-feldspars from deep seated igneous bodies are totally unreliable in the degree of their argon retention. Other minerals, e.g. beryl and some pyroxenes may show anomalously high argon contents. (York and Farquhar, 1972). The temperatures at which different minerals begin to retain radiogenic argon are different. The age given by a single mineral will be the time at which it became a closed system to radiogenic argon. In old rocks this is more likely to be related to the time of the last metamorphism or to the time of uplift and cooling of the rocks rather than the time of their formation.

K/Ar whole rock ages give an average of the individual apparent mineral ages for the rock. The apparent age for the rock will depend on the relative proportions of the constituent minerals and their argon retentivities. As a result K/Ar determinations are usually only carried out on separated minerals. Only when mineral separations are very difficult are whole rock analyses resorted to and then only for fine grained basic rocks with little or no K-feldspar content. In regions of old rocks it is seldom possible to find material that is sufficiently fresh and unmetamorphosed to yield an age of formation of the rock by this method.

The Rb/Sr Method

At the time of crystallization of the rock rubidium and strontium are incorporated into it. Radioactive ^{87}Rb decays to ^{87}Sr. The amount of radiogenic strontium formed since the time of formation of the rock may be used as a measure of the age of the rock provided there has been no loss or gain of rubidium or strontium during this time. It is assumed that the proportion of total rubidium that is ^{87}Rb at the present time is known and is essentially constant in different materials. It is also assumed that the decay constant for ^{87}Rb is known and that it has remained constant throughout geological time. Unfortunately, the decay constant for ^{87}Rb is not known precisely. Some geochronologists accept a value of $\lambda\,Rb = 1.39 \times 10^{-11}\ yr.^{-1}$ whilst others use $\lambda\,Rb = 1.47 \times 10^{-11} yr.^{-1}$. The former value gives results about

6% higher than the latter. Until a single value is acceptable to all geochronologists the most reasonable approach is to quote the decay constant used for each age determination rather than convert all determinations to one or other scale.

Single whole rock or mineral age determinations use the relationship:

$$Sr^{*} = {}^{87}Rb.\ \lambda\ Rb.t \quad \ldots\ldots (1)$$

obtained from the radioactive decay equation and approximately correct for all but the oldest rocks

where Sr^{*} = radiogenic strontium produced during time t

$\lambda\,Rb$ = decay constant for ^{87}Rb

t = time of formation of the rock before present

and ^{87}Rb = concentration of ^{87}Rb in rock at present.

Also $Sr^{*} = {}^{87}Sr$ present - ^{87}Sr initial

or $$Sr^{*} = {}^{86}Sr\left[\left(\frac{^{87}Sr}{^{86}Sr}\right)_{present} - \left(\frac{^{87}Sr}{^{86}Sr}\right)_{initial}\right] \ldots (2)$$

It is assumed that:

$$^{87}Rb = 0.2785\ .\ \text{total Rb} \quad \ldots\ldots (3).$$

Thus, if the present rubidium content is measured and also ^{86}Sr and the present $^{87}Sr:^{86}Sr$ ratio, then using equations 1, 2 and 3, t, the time of formation of the rock before the present may be obtained provided only that the initial $^{87}Sr:^{86}Sr$ ratio is known. Leutwein et al. in their work up to 1969 assumed that this ratio is constant and equal to 0.712. This assumption was universally made until the early 1960's. Adams (1967) assumed a "likely" value for this ratio based on his whole rock isochron data and geological information on a particular rock for the very few rocks he determined by this method.

Extensive work using the Rb/Sr whole rock isochron method now shows that the initial $^{87}Sr:^{86}Sr$ ratio is not the same for all rock types or for rocks of all ages and that considerable errors may arise in age determinations which make this assumption, particularly when the $^{87}Sr:^{86}Sr$ ratio has not increased much during the life-time of the rock.

Micas and particularly K-feldspar appear normally to have good qualities of retention of radiogenic strontium. However, as a result of metamorphism individual minerals may lose radiogenic strontium and it is inadvisable to assume an initial $^{87}Sr:^{86}Sr$ ratio for any single mineral particularly from rocks that may have suffered a later metamorphism.

The Rb/Sr whole rock isochron method takes the following form.

Combining equations 1 and 2 above we obtain:

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_{present} = \frac{^{87}Rb}{^{86}Sr} . \lambda t + \left(\frac{^{87}Sr}{^{86}Sr}\right)_{initial}$$

which is in the form of the equation of a straight line, $y = mx + c$.

If the present $^{87}Sr:^{86}Sr$ and $^{87}Rb:^{86}Sr$ ratios are determined in several whole rock samples they will plot on the same straight line provided certain important conditions are fulfilled. These necessary conditions are that all samples had the same initial strontium ratio, all are of the same age and, on the scale of the whole rock sample, all have remained closed systems to rubidium and strontium since the time of their formation. The slope, λt, of the line yields the age of the rocks and the intercept on the $^{87}Sr:^{86}Sr$ axis is the initial strontium isotope ratio.

To obtain a good isochron a wide spread of $^{87}Rb:^{86}Sr$ values is important. The rocks most likely to have this are granitic rocks or rocks rich in K-feldspar. For more basic rocks with a limited range of $^{87}Rb:^{86}Sr$ values the definition of the slope of the isochron is much less satisfactory.

If the individual minerals of a whole rock became closed systems with respect to ^{87}Rb and ^{87}Sr at the same time as the whole rock samples, and have remained so, then they also would plot on the whole rock isochron. If, however, they only became closed systems at a later time, for example on uplift and cooling, or if they later became open systems, for example during metamorphism, then the separate mineral isochron would record this later event. On the scale of the whole rock samples the system will usually have remained closed, even though particular minerals became open systems and the whole rock isochron will still indicate the age of formation of the rock despite the later metamorphism.

The Age of the Pentevrian

The rocks considered here are those collected from areas previously assigned to the Pentevrian on geological arguments of variable quality and also those which have yielded very old ages and, as a result, are considered to be Pentevrian.

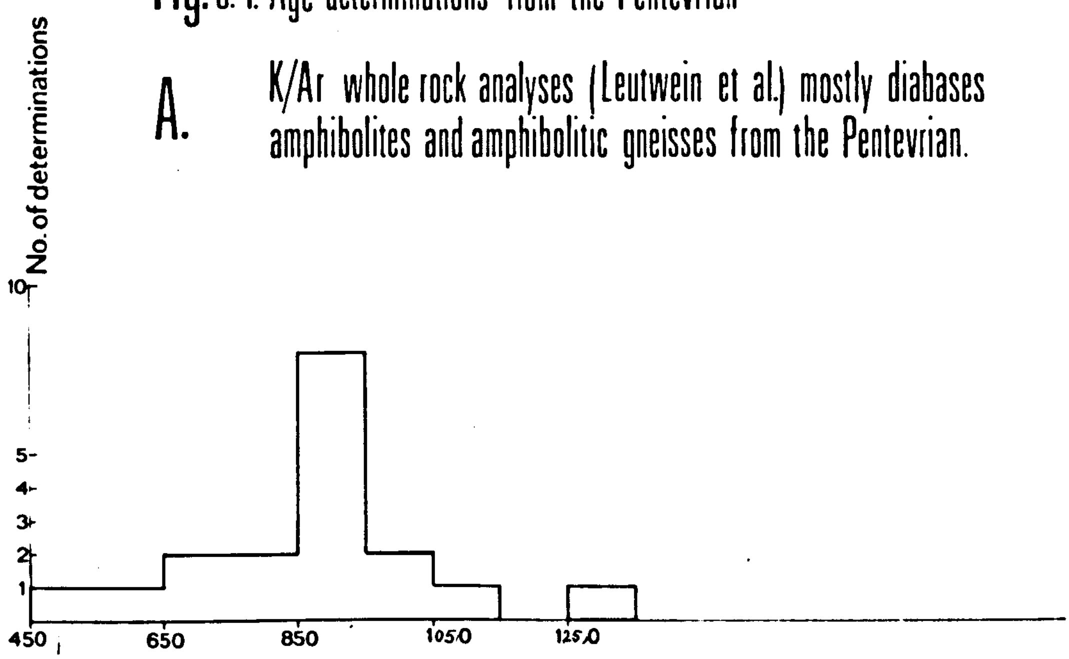
K/Ar Method

18 K/Ar whole rock results have been compiled from the available literature (Leutwein and Sonet, 1965; Leutwein, 1968a) (see figure 8.1). They are from basic rocks, the majority of which are from around the Baie de Saint-Brieuc (figure 1.2). The determinations show a spread from 460m.y. to 1265 m.y. Eight of the eighteen determinations fall in the interval between 850 and 950m.y. Only four of the determinations are between 950m.y. and 1265m.y. (980, 1050, 1090 and 1265 m.y.).

The spread of apparent ages is probably at least in part the result of variation in mineralogical composition of the samples. The 'younger' rocks may be those with a higher proportion of minerals

Fig. 8. 1. Age determinations from the Pentevrian

A. K/Ar whole rock analyses (Leutwein et al.) mostly diabases amphibolites and amphibolitic gneisses from the Pentevrian.

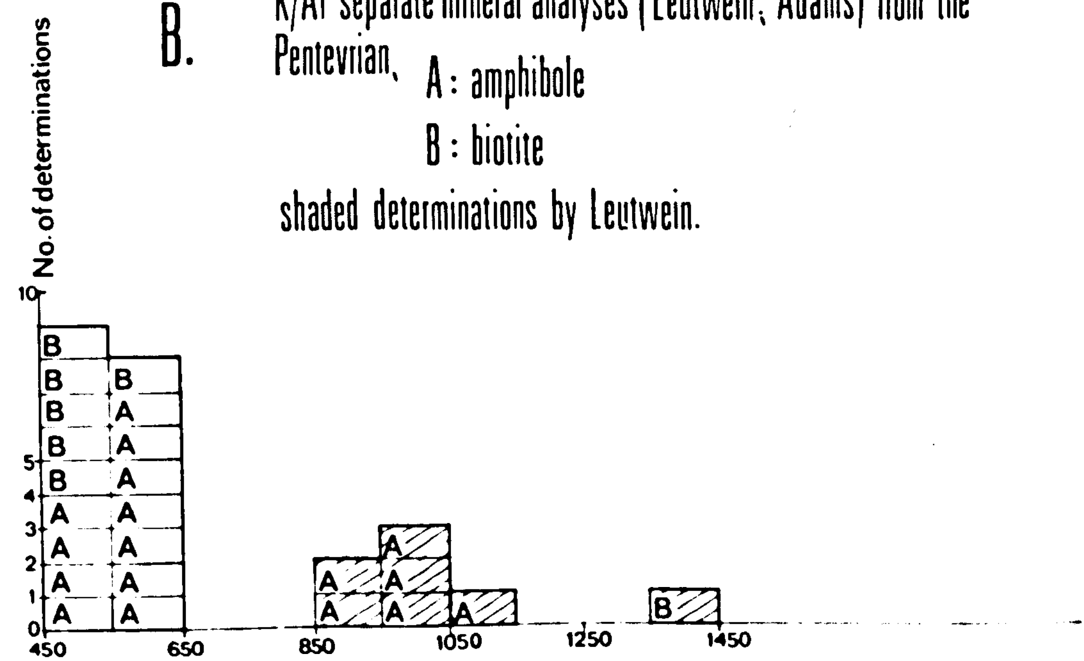


B. K/Ar separate mineral analyses (Leutwein, Adams) from the Pentevrian.

A : amphibole

B : biotite

shaded determinations by Leutwein.



with poor argon retaining properties. The sample yielding a 460m.y. date is a granodioritic gneiss and K-feldspar is known to have poor properties of argon retention. The majority of samples giving dates between 850 and 950m.y. are listed as being amphibolitic gneisses. However most of those with dates greater than 950m.y. are diabases which might be expected to show the worst properties of argon retention. Correlations of this type are of limited value and emphasise the difficulty in interpreting K/Ar whole rock determinations.

Assuming no excess argon is present, which is always a possibility, the apparent ages may be interpreted as indicating that some of the rocks are at least 950 to 1250m.y. old. It is probable that an event, either metamorphism or uplift, took place prior to 850-950m.y. ago giving rise to the 850-950m.y. apparent ages for a large proportion of the samples. The spread of dates suggests the probability of younger events.

Discounting any K-feldspar mineral dates, 23 published K/Ar mineral dates from the Pentevrian, 16 amphiboles and 7 biotites have been compiled (see figure 8.1). 7 determinations are by Leutwein (1965, 1968a, 1968b) and 16 by Adams (1967). Adams' samples are predominantly from the Channel Isles and fall between 500 and 600 m.y. They indicate a post-Pentevrian event as will be discussed later. Leutwein's determinations are from the Baie de Saint-Brieuc area and are grouped around 1000m.y. They date more closely the event giving rise to the 850-950m.y. apparent ages for the K/Ar whole rock determinations. It is encouraging to note that, for the two samples for which Leutwein gives both whole rock and separate mineral dates (S12, 162), there is close agreement between the two types of determination, indicating that the whole rock results are not markedly lower in age for those particular examples. Unfortunately, the three specimens analysed by Adams from Jospinet and Hillion all yielded ages between 500 and 600m.y. and failed to support the evidence for an event around the Baie de Saint-Brieuc at about 1000m.y. Thus, this Pentevrian event depends on the evidence of at the most 6 K/Ar mineral ages and about 10 K/Ar whole rock analyses. It is clear that it would be desirable to have many more published K/Ar separate mineral ages for the Saint-Brieuc area to define more closely events around this period of time.

Rb/Sr Method

Leutwein (1968a) gives 2 whole rock and 2 mineral dates in the range 790-900m.y. and one whole rock date of 1300m.y. from Pentevrian rocks. For all these determinations he assumed an initial strontium ratio of 0.712 and, as a result, the value of these determinations is doubtful. As Leutwein (1969) says, "Actuellement, il faut admettre que la datation par la methode Rb/Sr d'un minéral seul, appliquant de façon axiomatique le coeffient 0.712, ne donne qu'un chiffre à valeur chronologique problématique". This also applies to a lesser extent to single Rb/Sr whole rock determinations. Specimen JLB 9 from a microdiorite at Nez de Jobourg gave an age of 1300m.y. when an initial ratio of 0.712 was assumed (Leutwein, 1968a) but subsequently reanalysed (Leutwein et al. 1973) it plots on a Rb/Sr whole rock isochron with an age of 2504m.y. (λ Rb = 1.47×10^{-11} yrs.$^{-1}$) and an initial isotopic ratio of 0.7003. In this particular example the assumption of an initial ratio of 0.712 gave rise to an estimate of age only half that obtained by a whole rock isochron. Whilst it is not suggested that there need be such a large discrepancy in the other single specimen Rb/Sr determinations (as this will depend both on the error in assuming the initial strontium isotope ratio and the magnitude of the difference between the present and initial strontium ratios) there is no published information that shows just what the error is likely to be. Accordingly, it is considered inadvisable to use these determinations in any geochronological scheme.

Adams (1967) produced the first Pentevrian Rb/Sr whole rock isochron ages. These were for the Icart gneiss on Guernsey. The ages obtained depend heavily on Adams' interpretation of a problematical isochron. A scatter of points was obtained rather than all the points falling on a single straight line. Adams considered that all the assumptions implicit in the Rb/Sr whole rock isochron method could not have been fulfilled. However, he showed that the majority of the points might be divided into two sets, each forming a straight line plot. These lines gave ages of 2620m.y. and 1960m.y. ($\lambda_{Rb} = 1.39 \times 10^{-11} yr.^{-1}$). Furthermore, the points making up the older isochron were all from close to the margins of the gneiss and those making up the younger isochron from areas remote from the margins. Adams concluded that the two isochrons could not date two phases of gneiss formation since Roach (1957) had shown that all the gneisses were formed during the first phase of regional metamorphism. A second phase of regional metamorphism and deformation had affected the gneisses, but no new major rock-types were formed at this time. Therefore, Adams suggested that whilst the older age was possibly close to the true age of formation of the gneiss the younger age was of dubious significance and probably represented an isotopic redistribution at a later time. Roach et al. (1972) used the 2620m.y. age as evidence of a gneiss forming event which they called the Icartian and suggested the possibility of the younger age being correlated with the second deformational event called the Lihouan.

Roach (personal communication, 1974) has now revised his views on the sequence of geological events to have affected the gneisses of southern Guernsey. The Icart gneiss was emplaced during an early event which also produced a banding in the gneiss. This event is now called the Icartian. However, the main foliation was formed during a later event which was accompanied by amphibolite facies metamorphism. This main foliation was then deformed under upper greenschist facies conditions with only very local development of a new foliation. This new interpretation of the geological relations requires that a re-evaluation of the isochrons be made. Does the 2620m.y. isochron represent the time of emplacement of the gneiss or that of the formation of the main foliation in it? If there was complete rehomogenisation 2620m.y. ago at the time of formation of the main foliation or if the emplacement of the gneiss, formation of the banding and main foliation all took place very closely together in time, then the later folding may have taken place 1960m.y. ago. If, however, the gneisses were formed 2620m.y. ago it seems difficult to believe that they could have suffered amphibolite facies metamorphism and formation of a strong foliation without any recognisable isotopic redistribution, yet apparently suffer redistribution during a later upper greenschist facies metamorphism and fairly gentle deformation.

Thus, it is concluded that an important event may be recognised to have taken place 2620m.y. ago, but that it may not be unequivocally related to either emplacement of the gneiss or formation of the main foliation. The 1960m.y. isochron may indicate later redistribution of the strontium isotopes but cannot be linked directly with a specific event with any certainty.

Adams also obtained an intersection age on two specimens from Alderney, one of the Westerly quartz diorite and one of an associated aplite which together yielded an age of 2220m.y. (λ Rb = 1.39 x 10^{-11}yr.$^{-1}$).

Rocks from La Hague collected during work for this thesis have been dated by Leutwein (Leutwein et al., 1973) and these provide further examples of Pentevrian Rb/Sr whole rock isochrons. Gneisses from the Nez de Jobourg area and from the Omonville area fall on an isochron of 2504m.y. ($\lambda_{Rb} = 1.47 \times 10^{-11}$ yr.$^{-1}$), whilst three specimens of granitic gneiss from the Gréville area, together with Adams' two Alderney specimens, form an isochron of 2199m.y. ($\lambda_{Rb} = 1.47 \times 10^{-11}$ yr.$^{-1}$). Again, the specimens do not form two absolutely clear cut isochrons as one further specimen of the Gréville granitic gneiss (JLB 14) actually plots on the 2504m.y. isochron.

A preliminary announcement (Auvray and Vidal, 1973) has indicated another Rb/Sr whole rock isochron yielding a Pentevrian age. The Port-Béni gneiss of the Tregor, northern Brittany has given an age between 1000 and 2200m.y. ($\lambda_{Rb} = 1.47 \times 10^{-11}$ yr.$^{-1}$). Detailed information was not given, but it appears that again a spread of points may have been obtained rather than a single straight line.

It seems that the Rb/Sr whole rock isochrons obtained so far from the older Pentevrian rocks often yield a scatter of points rather than a single straight line. It may be that most of these Pentevrian rocks have not remained closed systems with respect to ^{87}Rb and ^{87}Sr. The situation is not helped by the general scarcity of fresh rocks of suitable composition and clear cut isochrons may prove impossible to obtain (Adams, 1967). The problem of successfully sampling a complex series of polycyclic metamorphic gneisses such as the Pentevrian gneisses should not be underestimated. Such sampling will only be successful when it has been preceded by extremely detailed geological studies to ensure that all the samples chosen to prepare an isochron are definitely of the same geological age, a necessary prerequisite of the Rb/Sr whole rock isochron method.

The Rb/Sr whole rock isochron evidence published to date suggests an important event around 2600m.y. ago ($\lambda_{Rb} = 1.39 \times 10^{-11} yr.^{-1}$). The ages between 2600m.y. and about 2000m.y. are not considered to have been firmly enough established yet to indicate the age of any particular younger event with any certainty. At the present state of our knowledge they may simply be taken to indicate that many of the gneisses did not remain closed systems to ^{87}Rb and ^{87}Sr. A late Pentevrian event has been suggested by 6 K/Ar mineral ages from around the Baie de Saint Brieuc at approximately 1000 m.y. and is supported by 10 K/Ar whole rock dates which fall in the general interval 850-950m.y. Evidence for this event has not yet been recorded from elsewhere or supported by Rb/Sr whole rock isochron determinations.

The Age of the St. Malo Migmatites

The St. Malo migmatites are considered by some (Brown, Barber and Roach, 1971) to be Pentevrian in age. Leutwein (1965, 1968a) published a series of single specimen Rb/Sr ages for separated minerals, biotite, muscovite and K-feldspar from the St. Malo migmatites. Unfortunately, as already discussed, the assumption of an initial strontium ratio of 0.712 particularly for single minerals makes the determinations of limited value. A Rb/Sr whole rock isochron is urgently needed to establish the age of the St. Malo rocks beyond question.

The Age of the Brioverian Sediments

K/Ar Method

Leutwein (Leutwein and Sonet, 1965; Leutwein, 1968a, 1968b; Leutwein et al., 1969) has published 20 K/Ar whole rock determinations mostly on basic dykes and spilitic lavas associated with the Brioverian sediments (see figure 8.2A). The apparent ages range

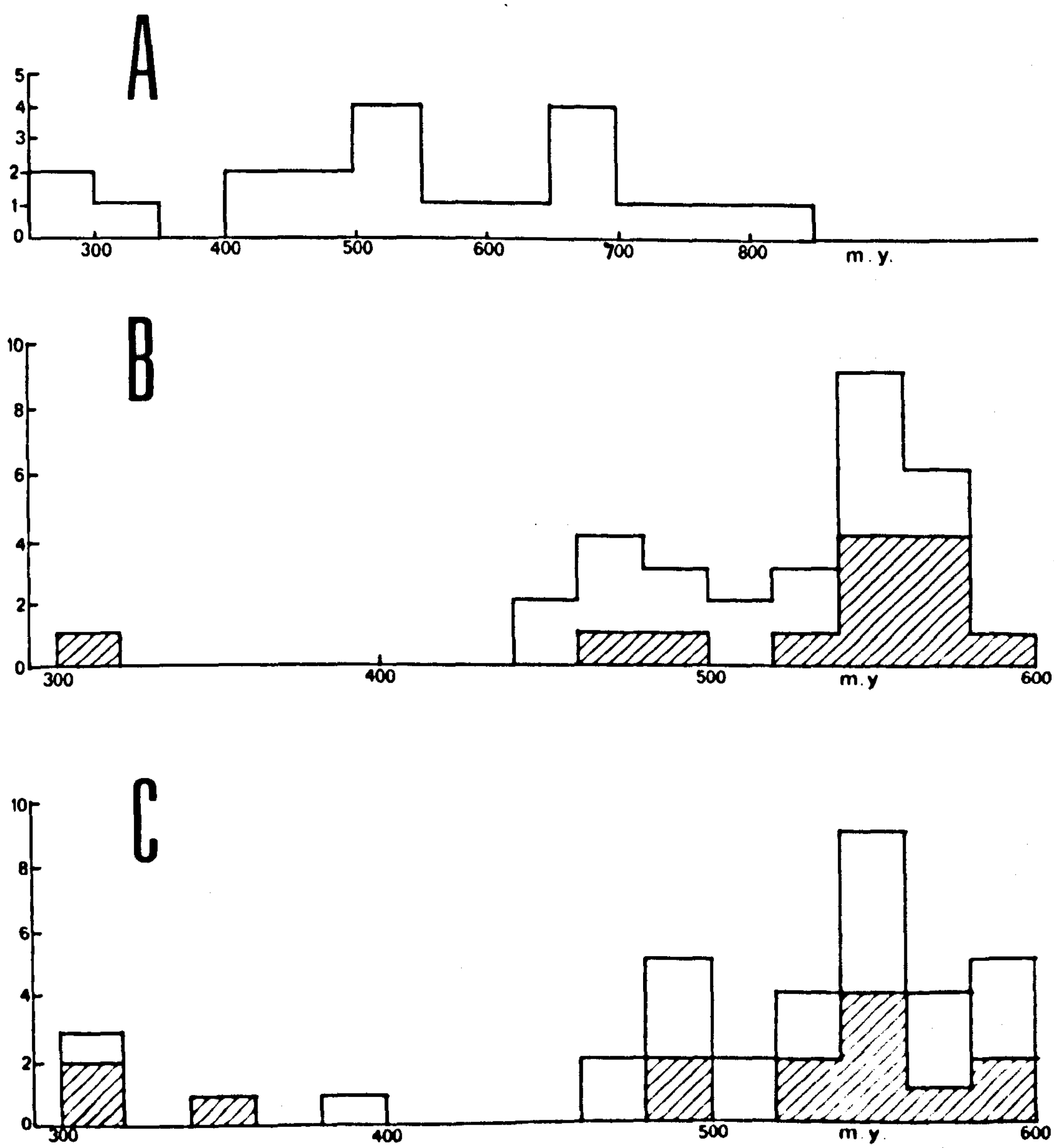
Fig. 8.2 Brioverian and Cadomian K/Ar determinations.

A. Whole rock on dykes and lavas in Brioverian sediments.

B and C. Mineral ages from Cadomian intrusives. (hatched – early Cadomian)

B. 32 Hornblende ages

C. 36 Biotite ages



from 300 to 770m.y. with one determination at 810m.y. Bearing in mind the limitations of the method and assuming excess argon was not present in the samples these results suggest that the beginning of Brioverian sedimentation took place at least 700m.y. and possibly 800m.y. ago.

Rb/Sr Method

Leutwein (1968a, 1968b; Leutwein et al., 1969) quotes Rb/Sr single whole rock results (assuming initial strontium isotope ratio is 0.712 and $\lambda_{Rb} = 1.47 \times 10^{-11} yr.^{-1}$) of 690m.y. for diabases from Erquy and La Ville Pichard and 630m.y. for schists from Plessala and 620m.y. for pillow lavas from Penn ar Vir. Given the uncertainties of the initial strontium isoptope ratio these values may at most only support the K/Ar whole rock determinations in a general way.

Vidal et al. (1971) provide a Rb/Sr whole rock isochron for the spilites and keratophyres of the spilitic sequence at Erquy. This yields a date of 466 ± 10m.y. ($\lambda_{Rb} = 1.47 \times 10^{-11} yr.^{-1}$) and is interpreted as the age of extrusion of the lavas, placing the rocks at Erquy in the Lower Ordovician. The interpretation of this isochron has been questioned by Brown and Roach (1972). They query whether the isochron age is likely to represent the age of extrusion of the lavas. The lavas appear to have suffered greenschist facies metamorphism and, as a result, may have undergone whole rock Sr isotope homogenisation at that time. They considered it difficult to explain the fact that Leutwein obtained K/Ar whole rock ages of 670 and 750m.y. for similar spilitic diabases from the La Ville Pichard - La Corderie and Plage de Saint Pabu near Erquy. Also, they point out that lithologically the rocks at Erquy are more like those of the Brioverian than the shallow water sediments characteristic of all the known Lower Palaeozoic rocks in north-west France.

Vidal et al. (1972) in reply to the criticisms of Brown and Roach claim that the mineral parageneses are primary. They point out the possibility of the presence of excess argon being contained in submarine lavas at the time of their extrusion as demonstrated for similar sequences elsewhere. This may result in K/Ar whole rock ages for rocks of this type being anomalously high. They also note the unusual difficulty in reconciling a Sr isotope homogenisation with apparently little effect on the K/Ar ages as implied by Brown and Roach's arguments. They admit they have no answer to the problems of lithological correlation.

If it is assumed that the interpretation of the isochron and the palaeontological evidence are irrefutably correct then it is only possible to look for explanations for the difficulties in geological correlation which arise if the Erquy spilites are Ordovician in age. However, in addition to the arguments given by Brown and Roach (1972) there are other reasons which suggest that caution should be exercised in the uncritical acceptance of the isochron as dating the time of formation of the Erquy volcanics.

Strong arguments have been presented that spilites may be basalts that have suffered post-consolidation alteration e.g. Vallance (1969), Cann (1969), Hughes (1973) and that differences in chemical composition between cores and selvedges of spilitic pillows originated at the time of this alteration. Certainly unaltered basalt pillows are often uniform in chemical composition (Vallance, 1969). Hart (1970) showed that basalts may develop zones of alteration with similar chemical trends to those of spilitic pillows by chemical exchange with sea water. It seems probable that chemical exchange of a similar type between rock and pore water would continue during subsequent burial or a later low grade metamorphism. Auvray and Hameurt (1971) gave chemical analyses of the same core and selvedge samples as used for the Erquy isochron. These show relative enrichment of the selvedges in Al_2O_3, Fe_2O_3, K_2O, Rb and H_2O and impoverishment in SiO_2, Na_2O and Sr compared with the cores, i.e. the classical differences often shown by spilitic pillows (Vallance, 1969). In addition, the samples all show greater than 2.5% H_2O which for basalts would be taken as a sign of extreme alteration. All this suggests that the samples of the Erquy pillow lavas may not have remained closed systems to Rb and Sr from the time of their formation. A similar argument may be applied to the keratophyre samples used for the isochron. Keratophyres may be the result of metasomatic alteration of rhyolites (Battey, 1955; Hughes, 1973) and if this is so for the Erquy keratophyres then they too may not have become closed systems to Rb and Sr until after the metasomatism had ceased.

There are examples in the literature which suggest that Rb/Sr whole rock isochrons on volcanic rocks may yield dates other than their age of formation. Fairbairn et al. (1966) obtained anomalously low dates for Precambrian volcanic rocks from the Atlantic Provinces of Canada, although it must be admitted there was considerable scatter of points on some of the isochrons. Hughes and Malpas (1971) showed that some, at least, of these rocks had suffered extensive metasomatism and supported the views of Fairbairn et al. (1966) that the low dates could be the result of movement of Rb. Cormier (1969), as a result of a much more detailed radiometric study on the Coldbrook Group, New Brunswick, suggested it was possible to distinguish the age of formation of these rocks from the age of a subsequent metamorphism.

If movement of Rb and Sr in the Erquy volcanics is a possibility, as seems likely, and if it continued during subsequent burial or metamorphism, the isochron obtained may simply indicate the time at which movement of Rb and Sr ceased. The good fit of the points on the Erquy isochron would indicate, in this case, that Rb and Sr were completely free to migrate through the rock up to this time.

As will be shown in the next section on the age of the Cadomian orogeny, Rb/Sr isochrons on rocks intrusive into the Brioverian sediments place a minimum age for the deposition and early deformation of the sediments at 690m.y. ($\lambda_{Rb} = 1.39 \times 10^{-11} yr.^{-1}$). This supports Leutwein's K/Ar whole rock determinations on the rocks from the Lower Brioverian which suggest the beginning of Brioverian sedimentation took place at least 700m.y. ago and possibly at least 800m.y. ago. However these are both minimum estimates for the beginning of Brioverian sedimentation. The only evidence that suggests a maximum age limit is the probable late Pentevrian event around 1000m.y. ago. No evidence of this event has so far been found in Brioverian rocks. If it is truly a late Pentevrian then Brioverian sedimentation cannot be older than 1000m.y. and was almost certainly completed before 700m.y.ago. The exact time of the beginning of sedimentation and its duration are not known within this interval.

The Age of the Cadomian Orogeny

Rb/Sr Method

Adams (1967) produced a number of Rb/Sr whole rock isochrons (using $\lambda_{Rb} = 1.39 \times 10^{-11} yr.^{-1}$) for intrusive igneous rocks associated with the Cadomian orogenic cycle, (see table 8.1). He divides them into three groups:

1. 690-630m.y. - early kinematic granites and gneisses emplaced before the main metamorphism
2. 605-565m.y. - post or late kinematic granites
3. 520-490m.y. - a group of entirely post-tectonic granites.

TABLE 8.1

CADOMIAN RB/SR WHOLE ROCK ISOCHRONS (ADAMS, 1967)

$(\lambda_{Rb} = 1.39 \times 10^{-11} yr.^{-1})$

	m.y.
Gneiss de Brest, Finisterre	690 (50)
L'Eree Adamellite, Guernsey	660 (25)
Sark gneisses	650 (100)
Ecréhous/Minquiers gneisses	630 (15)
Vire-Carolles granite	605 (15)
Cobo ademellite, Guernsey	570 (15)
Renards granite, Finisterre	565 (40)
S.W. granites, Jersey	565 (15)
S.E. granites, Jersey	520 (4)
N.W. granites, Jersey	490 (15)
Saint-Quay-Portrieux diorite	559 (27)
from Vidal et al. (1972)	$(\lambda_{Rb} = 1.47 \times 10^{-11} yr.^{-1})$

K/Ar Method

70 K/Ar separate mineral determinations from Cadomian intrusive rocks have been compiled from the literature (see figure 8.2). The main source is Adams (1967) with some contributions from Leutwein and from others. (Leutwein, 1968a; Leutwein et al., 1969; Leutwein et al., 1973; Kaplan, Leutwein, 1963; Graindor, Wasserburg, 1962.) No mineral dates greater than 600m.y. have been recorded, thus yielding a minimum age for the main Cadomian metamorphism. A spread of dates between 500 and 600m.y. probably reflects closure of the minerals to argon following the Cadomian orogeny and may correspond to slow uplift and

cooling. A cluster of dates around 480m.y. may indicate the influence of the entirely post-tectonic intrusive rocks. Dates around 300m.y., particularly for those samples from Finisterre, show the influence of the Variscan orogeny.

Summarising, the Gneiss de Brest (690 ± 50m.y.) is said to pre-date the main Cadomian metamorphism in Finisterre (Bishop et al., 1969) and the L'Eree adamellite (660 ± 25m.y.) is said to pre-date the main Cadomian metamorphism in Guernsey (Roach, in Adams, 1967). Thus an upper age limit for the main Cadomian metamorphism is provided by these ages and a lower age limit by the maximum K/Ar mineral ages of 600m.y. The late or post-tectonic intrusive ages around 570m.y. signal the end of the Cadomian orogeny and occur close to the Cambrian-Precambrian boundary.

The Age of the Thiebot Complex, La Hague

Leutwein et al. (1973) using rocks collected during work for this thesis produced an Rb/Sr whole rock isochron for the Thiebot complex. This yielded an age of 775 ± 20 m.y. using $\lambda_{Rb} = 1.47 \times 10^{-11} yr.^{-1}$ or using the same decay constant as Adams for a direct comparison with his results, 820m.y. It is difficult to obtain precise results working with rocks with the low $^{87}Rb/^{86}Sr$ ratios that these rocks have. One is left with a choice of interpretations. The conditions for the isochron method may not have been fulfilled and the date obtained may not represent the age of formation of the rocks. Further points on the upper end of the isochron are required to confirm the precision of the 820m.y. date.

If the date does represent the true age of formation of the complex then this either extends the length of the Cadomian orogeny or gives evidence of a very late Pentevrian event. Whichever of these may be correct the length of time available for Brioverian sedimentation would be significantly reduced and different from that adopted prior to the determination of this isochron.

Rb/Sr mineral and whole rock isochrons on samples from the Thiebot complex give ages of 580m.y. ($\lambda_{Rb} = 1.47 \times 10^{-11} yr.^{-1}$) which correlate well with K/Ar separate mineral ages and confirm the effect of uplift and cooling on the complex at the end of the Cadomian orogeny.

CHAPTER 9

SYNTHESIS OF EVENTS IN LA HAGUE AND COMPARISONS WITH ADJACENT AREAS

In this concluding chapter a generalised sequence of events for the Precambrian rocks of La Hague, based on the detailed information of the earlier chapters, is compared with the sequences of events in Precambrian rocks of nearby areas.

EVOLUTION OF THE PRECAMBRIAN ROCKS OF LA HAGUE

(All dates calculated using $\lambda_{Rb} = 1.39 \times 10^{-11} yr.^{-1}$).

Pentevrian Events

The earliest event for which any evidence has been preserved was the deposition of sediments of dominantly psammitic and semi-pelitic composition together with the formation of basic bodies, possibly lavas. This took place earlier than 2650m.y. ago.

This was followed by the emplacement of K-feldspar granites, intrusion of basic dykes and the earliest recorded deformation (D_1) which gave rise to regional formation of banded gneisses probably around 2650m.y. ago. The accompanying metamorphism (M_1) was of low pressure amphibolite facies type.

A second phase of deformation (D_2) accompanied by upper amphibolite facies metamorphism (sillimanite + almandine + muscovite) and migmatisation, formed the main foliation (S_2) now seen in the gneisses. The S_2 foliation strikes between north and east and is inclined fairly steeply towards the south-east. At a late stage during this event the Nez de Voidries quartz diorite and Nez de Jobourg granodiorite were emplaced.

Deformation (D_3) produced small asymmetric folds of variable style and degree of development. The main foliation (S_2) was deformed but no new foliation was formed and there was no recognisable accompanying metamorphism. This deformation may have been preceded and was certainly followed by emplacement of basic dykes.

<u>The Thiebot Complex</u>

Following the D_3 deformation the Moulinet and Jardeheu quartz diorites, Thiebot granodiorite and Red granite were emplaced in that order. Deformation (D_4) gave rise to an almost vertical, often nearly north-south trending foliation in these bodies. It also formed a foliation in the post-D_2 basic dykes and was accompanied by at least upper greenschist facies metamorphism giving an assemblage of plagioclase and hornblende in these dykes.

This was followed by intrusion and deformation producing the Omonville streaky gneisses.

<u>Note</u>: It has not proved possible to establish whether the intrusion and deformation of the Thiebot complex was a late Pentevrian or an early Cadomian event. The Rb/Sr whole rock isochron gave an imprecise date of 820m.y. and this may not be regarded as a reliable estimate of the age of the complex. If the Thiebot complex should be proved to be an early Cadomian intrusive event then the D_4 deformation may correspond to the main Cadomian deformation (D_{2S}).

The Brioverian sediments were deposited at this time or probably more likely before the emplacement of the Thiebot complex.

Cadomian Events

The Brioverian sediments suffered an early deformation (D_{1S}) and a metamorphic foliation (S_{1S}) was formed.

The main deformation (D_{2S}) resulted in the production of small scale recumbent folds and a foliation (S_{2S}). The shear foliation (S_H) in the Pentevrian gneisses was probably formed by this deformation.

Late Cadomian events included the intrusion and deformation of the Sabine diorite and possibly the Sary granodiorite, also the formation of small scale late kinks and open folds in the mica schists at Landemer. The St. Martin monzonite was probably intruded towards the end of the Cadomian orogeny.

This was followed by the emplacement of a series of post-tectonic granitic rocks, the Northern granites. These were intruded in the following order: meladiorite, leucodiorite, Houffet granodiorite, La Becchue quartz diorite, St. Germain granite and then the Cap de la Hague granodiorite and the Ecuty granite, although it was not possible to establish in which order these last two were emplaced.

The end of the Cadomian orogeny resulted in the uplift and cooling of the Precambrian rocks around 570m.y. ago. This was followed by post-tectonic molasse type Cambrian sedimentation.

Comments on the Generalised Sequence of Events

Comparison of tables 2.1, 4.1 and 5.1 shows that in each area of Pentevrian gneisses there is evidence for the early existence of sediments and granitic rocks. These now show a gneissose banding which has been deformed to produce the main foliation and this has later been deformed into asymmetric folds. The similarity of this sequence of features in each of the adjacent areas is the basis for the conclusion that they were all produced by one and the same series of events and that it is valid to draw up the generalised sequence of events given.

A problem that arises is the interpretation of the Rb/Sr whole rock isochrons produced by Leutwein et al. (1973). Rocks from both the Nez de Jobourg and Omonville area fall on the same isochron giving an age of 2650m.y. but rocks from the Gréville area appear to fall on a younger isochron with an age of 2330m.y. Thus, it would seem from this evidence that the Gréville gneisses are younger than those of the other areas. The geological evidence gives no support for this view and it is suggested that in the absence of further isotopic determinations on the Gréville gneisses, interpretations of this isochron should be made with caution. It is based on a very few samples and, although these were selected from areas where the effects of the later S_H foliation were apparently absent, it is possible that the age obtained represents a partial overprint of an older age by a later event.

Another difference between the areas of gneisses is the attitude of the L_2 lineation. The L_2 lineation results from the intersection of the early gneissose banding with the S_2 surface. In the Nez de Jobourg area the L_2 lineations tend to plunge towards the north-east whilst in the Omonville and Gréville areas they tend to plunge towards the south-west. This feature is unlikely to be the result of later deformation of the S_2 surfaces and may reflect the orientation of the S_1 surfaces forming a large scale synform before the D_2 deformation. Alternatively it could indicate a variation in the D_2 stress field for the areas or differential tilting of fault bounded blocks of the gneisses.

COMPARISONS OF EVENTS ESTABLISHED IN LA HAGUE AND THOSE OF ADJACENT AREAS

The Pentevrian Gneisses

It is inadvisable to attempt to make correlations over large distances between small, isolated areas of Pentevrian gneisses. However, comparisons will be made between La Hague and the nearby Channel Islands.

The sequence of events recorded for the Pentevrian gneisses of Guernsey (Roach, personal communication, 1974) shows many similarities with the sequence in La Hague. In both Guernsey and La Hague the oldest rocks that have been preserved are metasedimentary and metabasic rocks dating from before 2600m.y. ago. The Guernsey metasediments have a mineral assemblage including cordierite and andalusite. Thus the rocks of both areas may have suffered the same early low pressure amphibolite facies metamorphism.

Both the granitic gneisses on Guernsey and the gneisses of La Hague show evidence for the formation of an early banding and for a later deformation producing the main foliation under amphibolite facies metamorphic conditions. The gneisses from both areas yield Rb/Sr whole rock isochrons suggesting an important event around 2600m.y. ago.

The Nez de Voidries quartz dioritic gneiss and the Nez de Jobourg granodioritic gneiss in La Hague and the Perelle and Doyle gneisses in Guernsey all seem to have been emplaced at much the same period of time. They may all be part of the same phase of igneous activity that took place towards the end of the deformation that produced the main foliation in the gneisses. The Westerly quartz diorite of Alderney gave an Rb/Sr whole rock intersection age based on two specimens of 2220m.y. (Adams, 1967) and may also have been formed during this period of igneous activity. However this correlation is in need of further verification.

Folds with a similar style to those produced by the D_3 deformation in La Hague are found in the Icart gneiss on Guernsey.

The Sark Gneisses

The Sark gneisses are composed of hornblendic gneisses and of semi-pelitic gneisses making up a metamorphic and migmatitic complex and this has been intruded by later granitic bodies. An examination of the Sark gneisses (Gibbons, Parker and Power, unpublished work) suggests that the structural description given by Sutton and Watson (1957) may be extended and that the sequence of events on Sark bears many similarities with the sequence in the Pentevrian gneisses of nearby Guernsey and La Hague.

At Banquette on the north-east coast of Sark interlayered within the semi-pelitic gneiss are more massive quartzo-feldspathic units. This layering may reflect original differences in lithology in a series of sediments and is termed S_0. Within the semi-pelitic layers there is evidence for the formation of a gneissose banding (S_1) in the form of leucocratic segregations and this is taken to have been formed during an early deformation (D_1).

Both the S_0 and S_1 surfaces have been deformed by a later deformation (D_2). The S_0 quartzo-feldspathic layers have been partially transposed parallel to the S_2 foliation and sometimes strongly boudinaged, but F_2 fold hinges with nearly north-south trending fold axes may be seen defined by folded S_0 layers. The S_1 bands in the semi-pelitic layers have been deformed and may now be seen as isolated F_2 fold hinges with nearly north-south trending fold axes and with their axial planes parallel to the S_2 foliation. No convincing interference structures were found between D_1 and D_2 structures.

The earlier structures in the gneisses may be detected at Banquette and other areas e.g. Derrible Point because the D_2 deformation does not seem to have been uniformly developed throughout the Sark gneisses. At Port à la Jument on the west side of the island, for example, the S_2 foliation is very dominant and the earlier surfaces have been almost completely transposed parallel to it, although an intersection lineation L_2 may be seen formed by the intersection of the S_1 banding with the S_2 surface.

A third phase of deformation (D_3) has folded the S_2 foliation and these F_3 folds may be seen clearly on the east coast from Grève de la Ville to Banquette. They have nearly horizontal north-south trending fold axes and are asymmetric in form, often being antiforms with a gently inclined western limb and a steep east limb. It can be demonstrated that both the L_2 intersection lineations and the small F_2 fold hinges have been deformed around the F_3 folds. The foliated granitic bodies are considered to have been emplaced after the D_3 deformation and their foliation to have been formed during a D_4 deformation.

The first three phases of deformation described for the Sark hornblendic and semi-pelitic gneisses are very similar to those recorded in the Pentevrian gneisses of Guernsey and La Hague. It is not possible to correlate between these separate areas on the basis of structural sequence of events alone as similar sequences could be of different ages. The correlation between Guernsey and La Hague was strengthened by the similarities in the Rb/Sr whole rock isochron ages. Unfortunately, there is no Rb/Sr whole rock isochron for the hornblendic and semi-pelitic gneisses of Sark. However, the granitic gneisses which intrude the hornblendic and semi-pelitic gneisses have been dated at 650m.y. and from this age it has been suggested that the granitic gneisses are early Cadomian intrusive phases (Adams, 1967). As the hornblendic and semi-pelitic gneisses are older than the granitic gneisses it is possible that they are of Pentevrian age and because of their similar structural history they could be equivalent in age to the Pentevrian gneisses of Guernsey and La Hague.

If the Sark hornblendic and semi-pelitic gneisses are considered to have been formed by the Cadomian orogeny special pleading is required to account for them when compared with the low grade Brioverian sediments on Jersey. If they are considered to be Pentevrian they form a natural extension of the Pentevrian gneisses of Guernsey.

The Early Cadomian Igneous Intrusions and the Thiebot Complex

The early Cadomian intrusions dated by Adams (1967) range in age from 690-630m.y. However, it must be emphasised that because the $^{87}Rb/^{86}Sr$ values for the rocks were low and only covered a restricted range, the resulting isochrons have a rather low precision. The best defined isochron was that for the Gneiss de Brest, Finistère (690 ± 40m.y.). This intrusion has been shown to post-date the main Cadomian fold phase (as these folds are overprinted by the thermal aureole) but to pre-date the main Cadomian regional metamorphism (Bishop et al., 1969). These authors were forced, however, to postulate that the metamorphism was accompanied by deformation in order to explain the formation of the foliation in the gneiss.

For the other dated intrusions the relationships to the Cadomian orogeny are less readily determinable and they rely to a large extent on the age determinations to define them as early Cadomian intrusions. The Ecrehous and Minquiers are isolated reefs off the north and south coasts of Jersey respectively. The L'Eree adamellite contains what may be a large raft of Brioverian sediments, the Pleinmont rock, but otherwise is in faulted contact with the Icart and Perelle gneisses Roach (1966). The Sark granitic gneisses have been intruded into the hornblendic and semi-pelitic gneisses of uncertain, but probably Pentevrian, age.

The rocks of the Thiebot complex have no contacts with Brioverian sediments and it is not possible to determine directly their relationship to the Cadomian orogeny. However, it is interesting to make a comparison between the Sark granitic gneisses and those of the Thiebot complex. The Sark rocks are mainly of quartz dioritic composition, although the Creux Harbour gneiss is more granodioritic, and they are very similar petrographically and chemically to the Moulinet quartz diorite of the Thiebot complex. The Sark granitic gneisses were emplaced after the formation of the main foliation (S_2) in the hornblendic and semi-pelitic gneisses. The sheet-like form of the Sark granitic gneisses is controlled by the S_2 foliation in the country rock gneisses, although locally transgressive contacts and strongly cross-cutting veins may be seen. Stoped off inclusions of country rock gneiss in the granitic gneiss show the S_2 foliation. Similarly, the Thiebot complex cross-cuts the S_2 foliation in the gneisses of La Hague. It is difficult to find clear evidence but both the Sark granitic gneisses and the Thiebot complex almost certainly post-date a phase of asymmetric folding of the main foliation in the country rock gneisses. Finally, both the Sark granitic gneiss and the Thiebot complex suffered a deformation producing a nearly north-south trending foliation parallel to the main foliation in the surrounding gneisses.

Given all the above similarities and the imprecision of their respective isotopic age determinations it is very tempting to conclude that there is a strong relationship between the Sark granitic gneisses and those of the Thiebot complex and that they could well both be early Cadomian intrusive phases formed by the same general phase of igneous activity.

The Post-Tectonic Cadomian Igneous Intrusions

Large scale post-tectonic Cadomian granites, such as the Vire-Carolles granite mass and related intrusions, occur to the south of the Contentin peninsula. Further north, granitic rocks of this age are found in Jersey, Guernsey and Alderney. In the absence of confirmatory isotopic age determinations it seems reasonable to assign the Northern granitic rocks of La Hague to this period of igneous activity. They post-date the Thiebot complex gneisses, are unfoliated and yet are almost certainly older than the Cambrian sediments of La Hague.

There are broad similarities between the products of the igneous activity in the Channel Islands and in La Hague although in detail each intrusive sequence has its own particular characteristics. They often form a series from gabbro or diorite, to granodiorite and finally to a fairly differentiated granite. Within a single series there may be a number of recognisably different rock types, each occupying only a rather limited area e.g. the south-eastern granites of Jersey. Reaction between phases, particularly the earlier ones, is not uncommon e.g. the Central diorite, Alderney and the Ronez diorite, Jersey.

The similarity in the igneous activity of the Channel Islands and La Hague suggests a common source region for the production of the magmas and local reaction and differentiation to account for the local variation in rock types.

Post-Cadomian Uplift and Sedimentation

Isotopic data (Leutwein et al., 1973) supports the concept of uplift and cooling of at least the northern part of the Armorican massif around 570m.y. ago (Adams, 1967). The nature of the Cambrian sediments of La Hague is consistent with the suggestion of Sutton and Watson (1970) and Cogné (1970) that they may be interpreted as post-tectonic molasse type sediments.

Conclusion

It is concluded that there is a close similarity in geological history between the rocks of La Hague and those of the Channel Islands. There is evidence preserved in this fragment of the earth's crust for Precambrian events spanning a period of more than 2000m.y. The information provided in this study should be of use in wider reconstructions of these times.

APPENDIX

ANALYTICAL TECHNIQUES

Preparation of Rock Samples for Analysis

Initial Preparation

Fresh rock samples 1-2 Kg in weight were collected for analysis. After removal of a specimen for the preparation of thin-sections the rest of the rock was reduced to pieces about 2 cm in diameter using a fly-press fitted with steel jaws. Any weathered surfaces were rejected during this process. The pieces were then crushed to a coarse powder using a "Sturtevant" jaw crusher. At this stage, when appropriate, the coarse powder was split into two equal portions, one for mineral separation and the other for preparation of a powder for chemical analysis.

Preparation of Rock Powder for Chemical Analysis

500 g of the coarse rock powder was crushed in 100 g loads in a "Tema" swing mill fitted with a 250 ml "Colmonoy" pot for 20 seconds per load. The resulting fine powder was thoroughly mixed on glazed paper with a spatula knife and a single 100 g split drawn off and crushed for a further 70 seconds in the "Tema" mill. Tests showed that for an average rock of the type analysed over 98% of the resulting powder would pass through a 240 B.S.S. mesh sieve. The use of a "Colmonoy" pot precluded the use of the samples for the analysis of cobalt and nickel as contamination of these elements was introduced during the crushing process.

Preparation of Rock Samples for Mineral Separation

100 g samples of the coarse powder were crushed for eight seconds in the "Tema" mill and the fraction between 90 and 120 B.S.S.

mesh retained. This fraction was thoroughly washed in distilled water to remove adhering fine dust particles and dried.

Separation of K-feldspar

The separation of K-feldspar from the 90-120 B.S.S. mesh fraction was carried out in a series of stages. First, all magnetic minerals were removed with a magnet. Next, the fraction was run through an isodynamic magnetic separator, first at 10° side slope, 30° forward slope and a current of 0.3 amperes and then the light coloured non-magnetic fraction again with the same slope settings but a current of 1.5 amperes, thus achieving a separation into "light" and "dark" mineral fractions. The "light" fraction was made up mainly of quartz, plagioclase and K-feldspar. The K-feldspar was separated from the other minerals by flotation in heavy liquids. A mixture of bromoform (S.G.: 2.91) and NN dimethyl formamide (S.G.: 0.95) having a specific gravity of about 2.59 was prepared so that test grains of microcline and albite floated and sank in it respectively. Separation was carried out in conical funnels. After allowing a sample of the "light" fraction to come to equilibrium in the heavy liquid mixture the bottom fraction (plagioclase and quartz) was run off into a filter paper, the central portion, if any, run off separately, and then the top fraction (K-feldspar) carefully washed into a filter paper. The process was repeated until sufficient of the top fraction was collected. A further separation was carried out on the top fraction alone to improve the purity of the sample and it was finally washed in acetone and dried.

After an examination under a binocular microscope for purity and the retention of a small sample of the grains for reference the remainder was ground to a smooth powder with an agate pestle and mortar.

X-Ray Powder Diffraction Analysis

The cell parameters of the K-feldspars were determined using an X-ray powder diffraction technique and computer refinement by a least squares method. The details of the technique are based on those advocated by Wright and Stewart (1968) and Edmondson (1970).

About 0.05 g of K-feldspar powder was mixed with about 0.005 g of calcium fluoride (CaF_2 sintered at 700°C for 24 hours) and 1 ml of distilled water. After thorough agitation the suspension was allowed to settle for ten seconds and then drawn off with a dropper and spread evenly over a glass plate about 3 cm square. This was allowed to dry overnight and formed the sample mount for analysis.

A Siemens Kristalloflex IV diffractometer was used with the following operating conditions:

Excitation:	35Kv 20mA
Cu K_α radiation (nickel filter)	λ = 1.5405 Å
Aperture diaphragm:	0.3 mm
Detector diaphragm:	0.1 mm
Goniometer speed:	1°/min.
Chart recorder speed:	1 cm/min.
Measuring range:	4×10^3 impulses/min.
Time constant:	3
Statistical error:	5%.

Diffractometer recordings were made from 57° 2θ to 15° 2θ, a single run for each sample. All samples were mixed with CaF_2 as an internal standard (a = 5.4620 at 25°C). Calcium fluoride peaks at 28.28°, 47.02° and 55.77° 2θ were used as references and all peaks on the recording corrected to allow for any deviations that occurred from these values. Peaks were measured as near their tops as practical.

The computer program used to obtain the refined cell parameters was written by Dr. P. Collis of the Chemistry Department, University of Keele and it required an input of indexed reflections. Accordingly the following procedure was adopted to index the peaks for each diffractometer recording. It is based on the method used by Wright and Stewart (1968) and relies greatly on their tables 11, 12 and 13 which provide a guide for the indexing of K-feldspar phases. Only those reflections marked with a double star in these tables as being observed in all or nearly all patterns for a particular phase were used in the indexing procedure.

1. The region around 29^{o} 2θ was observed carefully. If a single sharp 131 reflection was present the potassic feldspar was indexed as having monoclinic symmetry with the aid of table 11 of Wright and Stewart.
2. If the 131 reflection was split into two peaks, 131 and $1\bar{3}1$, the feldspar was indexed as triclinic using either table 12 or 13 of Wright and Stewart depending on whether the separation of 131 and $1\bar{3}1$ indicated intermediate or maximum microcline and also on the best fit of all the other peaks to be indexed.
3. In other cases both a monoclinic and a triclinic phase were present in the same sample. Sometimes, when one phase was present in only a small amount relative to the other phase it was only possible to record the probable presence of more than one phase. However, it was often possible to index peaks as belonging to each phase. Inevitably, this approach must lead to some loss of accuracy as some peaks were the product of complete overlap of two reflections from the separate phases and the resultant peak did not give the

3. true position for the reflection of either phase. This is a limitation of the method and all cell parameters determined for mixtures of more than one phase must be regarded with caution.

4. The indexed peaks for each phase were used in an initial refinement of the cell parameters using the "Celfit" program of Dr. P. Collis. This provided the least squares best fit solution for the cell parameters, which depended on the quality of measurement of the indexed peaks and the correctness of initial indexing. The output from the program, besides including the direct and reciprocal cell parameters, gave the difference between the 2θ value observed for each peak and the 2θ value calculated using the computed cell parameters. These differences were carefully noted after the initial refinement and where any large differences were found the peak position and index were checked. If no errors of measurement were detected the reflection was not included in a final refinement of the cell parameters.

Tabulated X-Ray Powder Diffraction Results

In each table of results the following information is included:

a, b, c: direct cell parameters in angstrom units.

α, β, γ: angular relationship between direct cell parameters.

Standard errors for each of the above are given immediately below each value in the table. These errors only reflect the internal consistency of line measurements and not the true precision of the determination. Wright and Stewart (1968) concluded that the best estimate of the precision of their determinations was twice their standard errors.

	α^*	β^*	γ^*
265M		64.091	
265T	90.127	64.096	91.830
371M		63.962	
371T	91.290	64.037	90.788
233M		64.125	
233T	89.668	64.093	92.508
228T	89.723	64.151	91.617
231M		64.074	
231T	89.692	63.915	91.907
452M		64.291	
452T	90.086	63.891	92.016
378T	90.460	63.974	92.090
9916T	90.434	63.967	92.008
9915M		64.515	
9915T	89.952	63.553	91.365
9914T	90.225	64.078	91.661
450T	90.148	64.102	90.517

	α^*	β^*	γ^*
188T	90.794	64.180	90.195
991T	90.537	64.254	90.980
993T	90.253	64.066	91.795
167T	90.078	63.988	92.181
994T	90.345	64.231	91.988
995T	90.171	63.949	91.751
175T	89.984	64.239	91.039
664M		64.272	
664T	90.475	64.183	91.106
668M		63.922	
704M		63.752	
999T	90.025	63.969	91.414
80T	90.295	64.0	90.744
120M		63.530	
344T	90.169	64.022	90.640

	α^*	β^*	α^*
342M		63.861	
342T	91.747	63.797	90.087
341T	90.648	63.887	91.152
352M		63.661	
352T	90.378	63.713	90.671
332M		63.898	
332T	90.105	64.089	91.621
340M		64.093	
466T	90.257	64.010	90.893
467T	89.949	64.455	90.894
470T	89.929	64.035	91.827
356T	90.072	63.822	91.109
516M		63.936	

TABLE A.1

RECIPROCAL LATTICE PARAMETERS FOR POTASSIUM FELDSPAR PHASES DETERMINED

V: direct cell volume in cubic angstroms.

n: number of reflections used in the refinement.

Or%: proportion of orthoclase molecule in potassic phase estimated from V.

Δ : obliquity. (Goldsmith and Laves, 1954)

where $\Delta = 12.5 \left[d\,(131) - d\,(1\bar{3}1) \right]$

and d = interplanar spacing of reflecting planes.

The angular relationships of the reciprocal cell parameters α^*, β^* and γ^* for all phases determined are given in table A1.

Major Element Analysis by Chemical Methods

The major elements were determined by chemical methods using the techniques usually followed in the geochemical laboratories at Keele (Floyd, 1968, unpublished laboratory handbook). These methods are based on the work of Riley (1958), of Shapiro and Brannock (1962) and of Walsh and Howie (1967) but include modifications by Floyd. Two solutions were prepared for each sample. Solution A followed a sodium hydroxide fusion of the sample and solution of the fusion cake in dilute sulphuric acid and was used in the determination of silicon. Solution B followed attack on the sample by perchloric and hydrofluoric acids and was used for the determination of the majority of the other elements.

Silicon was determined on solution A using the molybdenum blue complex and spectrophotometric measurement at 812 mμ.

Manganese was determined on solution B by oxidation to permanganate and spectrophotometric measurement at 525 mμ.

Titanium was determined on solution B using the hydrogen peroxide complex and spectrophotometric measurement at 400 mμ.

Phosphorus was determined on solution B using the molybdenum blue complex and spectrophotometric measurement at 827 mμ.

Total iron content was determined on solution B using the dipyridyl complex and spectrophotometric measurement at 522 mμ.

Aluminium was determined on solution B as a complex of 8-hydroxyquinoline extracted in chloroform at pH 5 after complexing iron as the ferrous-dipyridyl complex. Spectrophotometric measurement was at 410 mμ.

Magnesium and calcium were determined on solution B using atomic absorption spectrophotometry in an air-acetylene flame.

Sodium and potassium were determined on solution B by flame photometry.

Ferrous iron was determined after solution of a separate portion of the sample by hydrofluoric acid and sulphuric acid and titration against standard potassium dichromate solution using diphenylamine sulphonate as an indicator.

Water was determined using a modified Penfield tube technique (Shapiro and Brannock, 1962) with sodium tungstate as a flux.

Samples of the United States Geological Survey reference rocks, GSP-I and G-2 and of the C.N.R.S., Nancy reference rocks, GH and DR-N were analysed at the same time as the samples from La Hague and the results obtained are given in Table A.2. They are compared with the average results listed in recent published compilations of results which included statistical data. The results obtained are nearly always within the quoted one standard deviation of the average value. The results obtained for silica and alumina tend to show the greatest deviations from the average values. It is not anticipated that there are any serious systematic errors in the La Hague analyses judging by these results for the international reference rocks.

	GSP-1 Average	GSP-1 this work	G-2 Average	s	n	G-2 This work	GH Average	s	n	GH This work	DR-N Average	s	n	DR-N This work
SiO_2	67.27	66.93	69.19	0.44	30	69.6	75.74	0.61	45	76.4	52.99	0.89	20	53.0
TiO_2	0.69	0.66	0.53	0.04	30	0.47	0.08	0.04	42	0.07	1.07	0.19	19	1.03
Al_2O_3	15.11	15.21	15.34	0.11	30	15.13	12.69	0.35	45	12.50	17.35	0.80	21	18.30
Fe_2O_3	1.77	1.84	1.08	0.17	26	1.26	0.45	0.20	23	0.58	3.96	0.52	8	3.73
FeO	2.30	2.25	1.44	0.13	26	1.42	0.83	0.11	23	0.78	5.36	0.30	10	5.44
MnO	0.04	0.03	0.03	0.02	28	0.03	0.05	0.01	41	0.04	0.22	0.03	16	0.23
MgO	0.95	0.98	0.78	0.14	30	0.75	0.07	0.10	41	0.01	4.50	0.35	22	4.33
CaO	2.03	2.03	1.98	0.10	30	1.91	0.73	0.13	45	0.72	7.09	0.30	23	6.78
Na_2O	2.88	2.76	4.15	0.24	30	4.05	3.86	0.22	38	3.96	3.02	0.21	18	3.05
K_2O	5.48	5.48	4.51	0.29	30	4.58	4.78	0.15	44	4.98	1.70	0.14	19	1.72
P_2O_5	0.28	0.28	0.14	0.03	28	0.13	0.01	0.014	26	0.01	0.31	0.18	14	0.21
H_2O^+	0.57	0.55	0.55	-	-	0.45	0.47	0.18	19	0.40	2.26	0.35	4	2.22
	99.37	99.00	99.72			99.84	99.76			100.45	99.83			100.04

s: one standard deviation, n: number of analyses on which average is based.
GSP-1 granodiorite, G-2 granite, data from Flanagan (1969)
GH granite, data from Roubault, Roche, Govindaraju (1970);
DR-N diorite, data from Roche, Govindaraju (1968).

TABLE A.2

RESULTS OBTAINED FOR U.S.G.S. AND C.N.R.S. NANCY REFERENCE ROCKS COMPARED WITH PUBLISHED AVERAGES

Major Element Analysis by X-Ray Fluorescence Methods

Certain of the major element analyses, notably those of the Omonville granitic gneiss, were carried out on a Philips PW 1410 X-ray spectrometer at the Department of Geology, Portsmouth Polytechnic. The method used was that described by Brown, Hughes and Esson (1973). Details of the instrumental conditions are given in Table A.3.

Ferrous oxide determinations were made using the usual titration method. H_2O was not determined and consequently the analyses are given calculated on a water-free basis. They are not, therefore, strictly comparable with the analyses by chemical methods although this difference is relatively minor, amounting to 1-2% and may be overlooked except for the most rigorous comparisons.

X-Ray Fluorescence Analysis for Trace Elements

The analyses were carried out on a Philips PW 1212 fully automatic spectrometer. This instrument may be programmed to perform a sequence of measurements and punch out the count rates on paper tape.

Sample Preparation

Samples were prepared by mixing 6 g of rock powder with 10-12 drops of a 2% aqueous solution of MOVIOL (a polyvinyl alcohol; Hoechst Chemicals). The mixture was pressed in a die with polished tungsten carbide facings to a pressure of 20 tons per square inch for four minutes. The pellets so formed were then cured for twelve hours at 110°C.

Calibration

The instrument was calibrated using a series of samples of a granodiorite rock powder containing known additions of "Specpure" compounds. The United States Geological Survey reference rocks G-2, GSP-1 and BCR-1 and the Centre National de la Recherche Scientifique, Nancy, reference rocks GA, GH and BR were analysed using the

Element	Tube	Kv	MA	Crystal	Collimator	Peak °2θ	Background	Counter	Lower Level	Window
Fe	W	30	10	LiF(200)	Fine	57.50	+2.0	Scint.	200	500
Mn	W	50	40	LiF(200)	Fine	95.19	+2.0	Scint. & Flow	200	500
Ca	Cr	20	5	LiF(200)	Fine	113.08	-3.0	Flow	200	500
Ti	Cr	25	15	LiF(200)	Fine	86.07	-2.0	Flow	200	500
Si	Cr	30	15	P.E.	Coarse	109.18	-4.0	Flow	200	500
Al	Cr	50	30	P.E.	Coarse	144.98	-5.5	Flow	200	500
K	Cr	30	20	P.E.	Fine	50.67	-1.6	Flow	200	500
P	Cr	50	40	P.E.	Fine	89.51	-3.5	Flow	200	280
Mg	Cr	50	40	RbA.P.	Coarse	44.48	+4.0	Flow	330	120
Na	Cr	50	40	RbA.P.	Coarse	54.32	+4.0	Flow	300	150

All counting times 20 seconds peak 20 seconds background except P, Mg, Na, 40 seconds on peaks.

TABLE A.3

INSTRUMENTAL CONDITIONS FOR MAJOR ELEMENT ANALYSIS BY X-RAY FLUORESCENCE calibrations obtained. Because the majority of the samples to be analysed were granitic or granodioritic in composition four of the reference rocks selected were of this composition but two basalts were also chosen to check the effects of mass absorption corrections.

Flanagan (1973) gives a compilation of the 1972 values obtained for the international reference samples and these are given in Table A.4 together with the results obtained in this work. In general the values compare very favourably.

Calculation of Results

The basic assumption was made that for a given element the fluorescent intensity (i.e. peak minus background) is directly proportional to concentration. By measuring the fluorescent intensity for samples with known additions of the element the relationship between fluorescent intensity and concentration can be obtained.

The fluorescent intensity also depends on the mass absorption coefficient of the sample. Under certain conditions this may be shown to be inversely proportional to scattered radiation. One of two methods depending on this relationship were used to correct for variation in the mass absorption coefficient of the samples. One measured the scattered background radiation (Andermann and Kemp, 1958) whilst the other measured the intensity of the Compton scattered portion of a molybdenum K_{α} primary beam (Reynolds, 1963).

If background was the same either side of the peak only one measurement was made and assumed to represent the background under the peak. However, when background varied either side of the peak then two backgrounds were measured and the background under the peak calculated assuming all three backgrounds lie on a straight line.

For certain elements the fluorescent intensity measured required correction for coincidence of other fluorescent radiation. For

	G-2		GSP-1		BCR-1		GA		GH		BR	
	Recom-mended value	This work	Recom-mended value	This work	Recom-mended value	This work	Recom-mended Value	This work	Recom-mended value	This work	Recom-mended value	This work
Rb	168	188	254	281	47	47	175	189	390	390	45	43
Ba	1870	1982	1300	1330	675	717	850	869	22	28	1050	1049
Pb	31	38	51	64	18	18	*	34	*	49	*	7.8
Sr	479	514	233	250	330	336	305	330	10	11	1350	1304
La	96	107	191	159	26	29	36	30	25	21	85	89
Ce	150	178	394	368	54	43	*	56	*	53	*	133
Nd	60	59	188	131	29	42	*	26	*	32	*	65
Y	12	2.5	30	17	37.1	33	18	20	70	79	27	26
Th	24	23	104	110	6	1.5	15	13	*	83	*	8.4
U	2.0	0.6	1.96	2.1	1.74	1.2	*	4.4	*	17	*	3.3
Zr	300	313	500	538	190	188	140	135	160	161	240	227

* denotes insufficient analyses available for a value to be recommended.

TABLE A.4

COMPARISON OF 1972 'RECOMMENDED VALUES' FOR INTERNATIONAL REFERENCE SAMPLES (FLANAGAN, 1973) AND RESULTS OBTAINED IN THIS WORK example, Sr K_β coincides with Zr K_α. Correction was made by calibrating the increase in Sr K_β fluorescent radiation for known additions of strontium. Then for any sample having determined the strontium content the fluorescent radiation due to Sr K_β at Zr K_α could be calculated.

In routine use the spectrometer carries out a particular measurement first on a standard sample and then on three unknowns before proceeding to the next measurement in the sequence. The standard is included each time to allow correction for instrumental drift. This correction may be carried out by the instrument when it is operated in the fixed count mode. The time taken to accumulate the fixed count on the standard is automatically taken as the counting time on the unknowns. Alternatively, if the fixed time mode is used the correction is calculated and the count on the unknowns adjusted to allow for the percentage deviation of the standard from a previously determined "average" count on the standard.

The data obtained as punched tape output was processed on a Digital Equipment Company PDP/8S computer using the FOCAL symbolic language. The programs used were written by J.P. Sedgley and full details are maintained in the geochemical laboratories at Keele.

Instrumental Conditions

Full details of the instrumental settings used are summarised in Table A.5.

During the calibration all addition standards were measured six times and the mean values used to determine the least - squares best fit calibration slope. Duplicate determinations were made on all unknown samples.

Nd and La

For each of these elements a simple technique was followed with

Element	Rb	Sr	Y	Zr	La	Nd	Ce	Ba	U	Th	Pb
Line	K_α	K_α	K_α	K_α	L_α	$L_{\beta 1,4}$	$L_{\beta 1,4}$	$L_{\beta 1,4}$	L_α	L_α	$L_{\beta 1,2}$
Peak	37.87	35.73	33.78	31.92	82.95	99.15	111.80	128.85	37.33	39.28	40.44
Background	38.32	36.34	34.90	32.82	81.90	100.26	110.40	126.00	36.90	37.62	40.04
Background	36.34	34.90	32.82	31.53	-	-	-	-	37.62	40.04	40.70
Collimator	Fine	Fine	Fine	Fine	Coarse	Coarse	Coarse	Coarse	Fine	Fine	Fine
Crystal	Lif220	Lif220	Lif220	Lif220	Lif200	Lif220	Lif220	Lif220	Lif220	Lif220	Lif220
Detector	Scint.	Scint.	Scint.	Scint.	Flow	Flow	Flow	Flow	Scint.	Scint.	Scint.
Time (Secs)	40	40	40	40	F.C.	F.C.	F.C.	F.C.	40	40	40
Counts	F.T.	F.T.	F.T.	F.T.	10^4	10^4	10^4	3.10^4	F.T.	F.T.	F.T.
KV, mA	80,24	80,24	80,24	80,24	80,24	80,24	80,24	80,24	80,24	80,24	80,24
Window	External	External	External	External	160	External	160	160	External	External	External
Lower Level					420		420	420			
Tube	W	W	W	W	W	W	W	W	Mo	Mo	Mo

F.T.: Fixed time; W: Tungsten target; Mo: Molybdenum target.

TABLE A.5

INSTRUMENTAL PARAMETERS FOR X.R.F. TRACE ELEMENT ANALYSES one background measurement and no mass absorption corrections.

Calibration slope for Nd $L_{\beta 1}$ = 42.47 ± 0.65

" " " La L_{α} = 59.97 ± 0.81

Ce and Ba

Ce and Ba were determined in the same operating sequence so that Ba $L_{\beta 1,4}$ could be corrected for interference by Ce L_{α}. Apart from this correction a simple technique was followed with no mass absorption corrections.

Calibration slope for Ce L_{β} = 35.63 ± 0.29

" " " Ba $L_{\beta 1,4}$ = 25.07 ± 0.22

" " " Ce correction at Ba $L_{\beta 1,4}$

= 29.70 ± 0.80

U, Th and Pb

For each of these elements background under the peak was calculated using background measurements on each side of the peak and mass absorption corrections were made using the Mo K_{α} Compton scatter method (Reynolds, 1963).

Calibration slope for U L_{α} = 30.90 ± 0.30

" " " Th L_{α} = 25.49 ± 0.11

" " " Pb $L_{\beta 1,2}$ = 23.17 ± 0.14

Rb, Sr, Y and Zr

These four elements were determined in the same sequence. Thus by measuring five background positions the background under each peak could be calculated. In addition, Y K_{α} could be corrected for Rb K_{β} overlap and Zr K_{α} for Sr K_{β} overlap. Mass absorption corrections were made by the scattered background ratio method (Andermann and Kemp, 1958).

Calibration slope for Rb K_α = 0.01502

" " " Sr K_α = 0.01381

" " " Y K_α = 0.01199

" " " Zr K_α = 0.009938

" " " Rb K_β at Y K_α = 0.002892

" " " Sr K_β at Zr K_α = 0.001138

REFERENCES

Adams C.J.D. 1967. Earth Planet. Sci. Letters 2, 52-56. K/Ar ages from the basement complex of the Channel Islands (United Kingdom) and the adjacent French mainland.

Adams C.J.D. 1967. D.Phil. Thesis Univ. Oxford. A geochronological and related isotopic study of rocks from North-Western France and the Channel Islands (United Kingdom).

Andermann G., Kemp J.W. 1958. Anal. Chem. 30, 1306-1309. Scattered X-rays as internal standards in X-ray emission spectroscopy.

Auvray B., Hameurt J. 1971. Bull. Soc. Géol. Minéral. Bretagne, C, 3 (2), 59-76. Les caracteres chimiques de la serie spilitique d'Erquy (Bretagne septentrionale).

Auvray B., Vidal P. 1973. Réunion Annuelle Sciences de la Terre p54. Chronologie des évènements géologiques dans le Trégor (Bretagne septentrionale).

Battey M.H. 1955. Geol. Mag. 92, 104-126. Alkali Metasomatism and the Petrology of some Keratophyres.

Barrois C. 1895. Annl. Soc. Géol. N. 23, 38-46. Le calcaire de Saint-Thurial.

Bell T.H., Etheridge M.A. 1973. Lithos 6, 337-348. Microstructure of mylonites and their descriptive terminology.

Bertrand L. 1921. Flammarion, Paris, 188p. Les anciennes mers de la France et leurs dépôts.

Bigot A. 1882. Bull. Soc. Linn. Normandie (3) 6, 44-65. A Travers La Hague.

Bigot A. 1900. Carte Géologique de France. No. 16, "Les Pieux" 1:800,000.

Bigot A. 1904. Bull. Soc. Géol. Fr. (4) 4, 861-908. Réunion extraordinaire de la S.G.F. en Basse-Normandie.

Bigot A. 1929. C.R. Somm. Soc. Géol. Fr. 181-200. Réunion extraordinaire de la S.G.F. en Basse-Normandie et dans les Côtes-du-Nord du 11 au 19 Septembre 1929.

Bigot A. 1934. Bull. Soc. Linn. Normandie (8) 7, 19-38. Notice explicative de la deuxième édition de la Feuille Les Pieux de la Carte géologique de la France.

Bigot A., Jérémine E. 1923. C.R. Acad. Sci., Paris 176, 221-222. Observations nouvelles sur la géologie de la Hague (Manche).

Bishop A.C., Bradshaw J.D., Renouf J.T., Taylor R.T. 1969. Q. Jl. Geol. Soc. Lond. 124, 309-348. The stratigraphy and structure of part of west Finistère, France.

Boyer, C., Roblot M-M., Graindor M-J. 1972. C.R. Acad. Sci., Paris, D, 274, 21-23. Les ignimbrites du Post-Briovérien de Saint-Germain-le-Gaillard (Manche).

Bradshaw J.D., Renouf J.T., Taylor R.T. 1967. Geol. Rdsch. 56, 567-596. The development of Brioverian structures and Brioverian/Palaeozoic relationships in west Finistère (France).

Brown G.C. 1973. Nature Physical Science 241, No. 106, 26-28. Evolution of granite magmas at destructive plate margins.

Brown M., Barber A.J., Roach R.A. 1971. Nature Physical Science, 234, No. 47, 77-79. Age of the St. Malo Migmatite Belt, Northern Brittany.

Brown G.C., Fyfe W.S. 1970. Contrib. Mineral. Petrol. 28, 310-318. The production of granitic melts during ultrametamorphism.

Brown, G.C., Hughes D.J., Esson J. 1973. Chem. Geol. 11, 223-229. New X.R.F. data retrieval techniques and their application to U.S.G.S. standard rocks.

Brown M., Roach R.A. 1972. Nature Physical Science 237, 77-79. Brittany: Some comments on the Precambrian rocks south of Erquy and around St. Cast, Côtes-du-Nord.

Cann J.R. 1969. J. Petrology 10, 1-19. Spilites from the Carlsberg Ridge, Indian Ocean.

Chauris L., Dangeard L., Graindor M-J., De Lapparent A.F. 1956. C.R. Acad. Sci., Paris, D, 243, 77-79. Les principaux batholites granitiques du Bocage normand sont antérieurs à la transgression cambrienne.

Chinner G.A. 1961. J. Petrology 3, 316-340. The origin of sillimanite in Glen Clova, Angus.

Coates A.G. 1961. Bull. Soc. Linn. Normandie (10) 1, 87-90. Interprétation tectonique du synclinal de Jobourg (Manche).

Coates A.G. 1965. Ph.D. Thesis Kings College, London. The geology of the Jobourg and Siouville Synclines, Manche, France.

Cogné J. 1959. Bull. Soc. Géol. Fr. (7) 1, 112-118. Données nouvelles sur l'Antécambrien dans l'Ouest de la France: Pentévrien et Briovérien en baie de Saint-Brieuc (Côtes du Nord).

Cogné J. 1962. Bull. Soc. Géol. Fr. (7) 4, 413-430. Le Briovérien.

Cogné J. 1970. Colloque international sur les corrélations du Précambrien, Rabat. Le Briovérien et le cycle orogénique cadomien dans le cadre des orogènes fini-précambriens.

Cormier R.F. 1969. Can. J. Earth Sci. 6, 393-398. Radiometric dating of the Coldbrook Group of Southern New Brunswick.

Curtis C.D., Brown P.E. 1969. Contrib. Mineral. Petrol. 24, 275-292. The metasomatic development of zoned ultrabasic bodies in Unst, Shetland.

Curtis C.D., Brown P.E. 1971. Contrib. Mineral. Petrol. 31, 87-93. Trace element behaviour in the zoned metasomatic bodies of Unst, Shetland.

Dietrich R.V. 1962. Norsk. Geol. Tidsskr. 42, 394-414. K-feldspar structural states as petrogenetic indicators.

Deunff J., Auvray B., Cogné J., Hameurt J., Jeannette D., Vidal P. 1973. C.R. Acad. Sci., Paris, D, 276, 935-937. Confirmation micropaléontologique de l'âge radiométrique ordovicien inférieur du groupe spilitique d'Erquy (Côtes-du-Nord).

Edmondson K.M. 1970. M.Sc. Thesis University of Keele. A study of the alkali feldspars from some S.W. England granites.

Fairbairn H.W., Bottino M.L., Pinson W.H., Hurley P.M. 1966. Can. J. Earth Sci. 3, 509-521. Whole rock age and initial Sr^{87}/Sr^{86} of volcanics underlying fossiliferous Lower Cambrian in the Atlantic Provinces of Canada.

Faure G., Powell J.L. 1972. Strontium Isotope Geology. Springer-Verlag, Berlin.

Fischer K. 1970. In: K.H. Wedepohl (Ed.) Handbook of geochemistry Volume 2-3, Springer-Verlag, Berlin. 56. The geochemistry of barium.

Flanagan F.J. 1969. Geochim. Cosmochim. Acta 33, 81-120. U.S. Geological Survey standards - II. First compilation of data for the new U.S.G.S. rocks.

Flanagan F.J. 1973. Geochim. Cosmochim. Acta 37, 1189-1200. 1972 values for international geochemical reference samples.

Goldsmith J.R., Laves F. 1954. Geochim. Cosmochim. Acta 5, 1-19. The microcline-sanidine stability relations.

Graindor M-J. 1957. Mém. Serv. Carte Géol. Fr. 211p. 26pl. 45 figs. Le Briovérien dans le Nord-Est du Massif Armoricain.

Graindor M-J. 1958. Bull. Serv. Carte Géol. Fr. 56, No. 255 (C.R. Collab. 1957), 37-48. Remarques sur le déversement du Synclinal de Siouville.

Graindor M-J. 1959. C.R. Somm. Séanc. Soc. Géol. Fr. Réunion Extraordinaire Basse-Normandie 21-26 Sept. 1959.

Graindor M-J. 1960a. Bull. Soc. Linn. Normandie 1, 44-46. Existence vraisemblable du Penthevrien dans les Iles Anglo-Normandes et la Hague.

Graindor M-J. 1960b. Bull. Serv. Carte Géol. Fr. 57, No. 262, 475-549. Géologie du Nord-Ouest du Contentin.

Graindor M-J. 1961. Bull. Soc. Linn. Normandie (1960) 1, 9-13. Accidents tectoniques dans le Grès Armoricain à Cherbourg.

Graindor M-J. 1964. Geol. Rundsch. 54, 61-82. Les tillites Anté-Cambriennes de Normandie.

Graindor M-J., Wasserburg G.J. 1962. C.R. Acad. Sci., Paris, D, 254, 3875-3877. Determinations d'âges absolus dans le Nord du Massif Armoricain.

Hart R. 1970. Earth Planet. Sci. Letters 9, 269-279. Chemical exchange between sea water and deep ocean basalts.

Hill E. 1889. Q. Jl. Geol. Soc. Lond. 45, 380-390. On the rocks of Alderney and the Casquets.

Holdaway M.J. 1971. Amer. J. Sci. 271, 97-131. Stability of andalusite and the aluminium silicate phase diagram.

Hughes C.J. 1973. Geol. Mag. 109 (1972), 513-527. Spilites, keratophyres and the igneous spectrum.

Hughes C.J., Malpas J.G. 1971. Proc. Geol. Ass. Can. 24, 85-93. Metasomatism in the Late Precambrian Bull Arm Formation in south-eastern Newfoundland: recognition and implications.

Jeannette D., Cogné J. 1968. C.R. Acad. Sci., Paris, D, 266, 2211-2214. Une discordance majeure au sein du Briovérien au flanc Ouest de la Baie de Saint-Brieuc.

Jérémine E. 1924. C.R. Congr. Soc. Sav. Paris Sect. Sci. 3. Le granite à enclaves de la Hague.

Jérémine E. 1927. C.R. Congr. Soc. Sav. Paris Sect. Sci., 65-68. Dolérites et lamprophyres de la Hague (Manche).

Jérémine E. 1930. Bull. Soc. Géol. Fr. (4) 30, 3-50. Étude petrographique de la Hague.

Jérémine E. 1942. Bull. Soc. Géol. Fr. (5) 12, 21-25. A propos d'un schiste à sillimanite près de Jerdheux (Hague).

Kaplan G., Leutwein F. 1963. C.R. Acad. Sci., Paris, 256, 2006-2008. Contribution à l'étude géochronologique du massif granitique de Vire (Normandie).

Klein C. 1963. C.R. Somm. Séanc. Soc. Géol. Fr., 309-311. A propos de la carte géologique de Cherbourg au 50.000.

Leutwein F. 1968a. Can. J. Earth Sci. 5, 673-682. Contribution à la connaissance du précambrien récent en Europe Occidentale et développement géochronologique du Briovérien en Bretagne (France).

Leutwein F. 1968b. Sci. Terre, Nancy. Mém. 11. 84p. Géochronologie et évolution orogénique précambrienne et hercynienne de la partie nord-est du Massif Armoricain.

Leutwein F., Sonet J. 1965. Sci. Terre, Nancy 10 (1964-65), 345-366. Contribution à la connaissance de l'évolution géochronologique de la partie nord-est du Massif Armoricain français.

Leutwein F., Chauris L., Sonet J., Zimmermann J-L. 1969. Sci. Terre, Nancy 14, 329-358. Études géochronologiques et géotectoniques dans le Nord-Finistère (Massif Armoricain).

Leutwein F., Power G., Roach R., Sonet J. 1973. C.R. Acad. Sci., Paris, D, 276, 2121-2124. Quelques résultats géochronologiques obtenus sur des roches d'âge précambrien du Contentin.

Marmo V. 1967. Bull. Comm. Géol. Finlande 227, 83p. On granites; a revised study.

Morgan W.R. 1957. M.Sc. Thesis Univ. Nottingham. The igneous and sedimentary rocks of Alderney.

Nagger M.H., Atherton M.P. 1970. J. Petrology 11, 549-589. The composition and metamorphic history of some aluminium silicate-bearing rocks from the aureoles of the Donegal granites.

Nockolds S.R., Allen R. 1953. Geochim. Cosmochim. Acta 4, 105-142. The geochemistry of some igneous rock series.

Parsons I., Boyd R. 1971. Mineralog. Mag. 38, 295-311. Distribution of potassium feldspar polymorphs in intrusive sequences.

Peacock M.A. 1931. J. Geol. 39, 54-67. The classification of igneous rock series.

Presnall D.C., Bateman P.C. 1973. Geol. Soc. Am. Bull. 84, 3181-3202. Fusion relations in the system $NaAlSi_3O_8$-$CaAl_2Si_2O_8$-$KAlSi_3O_8$-SiO_2-H_2O and generation of granitic magmas in the Sierra Nevada Batholith.

Ragland P.C. 1970. Lithos 3, 167-189. Composition and structural state of the potassic phase in perthites as related to petrogenesis of a granitic pluton.

Ramsay J.G. 1960. J. Geol. 68, 75-93. The deformation of early linear structures in an area of repeated folding.

Read H.H. 1934. Mineralog. Mag. 23, 519-540. On zoned associations of antigorite, talc, actinolite, chlorite and biotite in Unst, Shetland Islands.

Reynolds R.C. 1963. Amer. Mineral. 48, 1133-1143. Matrix corrections in trace element analysis by X-ray fluorescence: estimation of the mass absorption coefficient by Compton scattering.

Riley J.P. 1958. Anal. Chim. Acta 19, 413-428. The rapid analysis of silicate rocks and minerals.

Roach R.A. 1957. Ph.D. Thesis Univ. Nottingham. The geology of the metamorphic complex of south and central Guernsey.

Roach R.A. 1966. Rep. Soc. Guernés. 18, 751-776. Outline and guide to the geology of Guernsey.

Roach R., Adams C., Brown M., Power G., Ryan P. 1972. 24th. Intern. Geol. Congress, Montreal, 1972, Section 1, 246-252. The Precambrian Stratigraphy of the Armorican Massif, N.W. France.

Robardet M. 1970. Bull. Soc. Géol. Fr. (7) 12, 15-22. Étude tectonique de la partie centrale de la zone Bocaine (Normandie).

Robertson J.K., Wyllie P.J. 1971. Amer. J. Sci. 271, 252-277. Rock water systems with special reference to the water-deficient region.

Roblot M.M. 1962. C.R. Acad. Sci., Paris, 254, 3720-3722. Sur une coupure stratigraphique à l'intérieur du Briovérien.

Roubault M., La Roche H. (de), Govindaraju K. 1970. Sci. Terre, Nancy 15, 351-393. Etat actuel (1970) des études coopératives sur les standards géochimiques du Centre de Recherches Pétrographiques et Géochimiques.

La Roche H.(de), Govindaraju K. 1968. Bull. Soc. Fr. Cér. No. 85, 35-50. Rapport sur deux roches, Diorite DR-N et Serpentine UB-N proposées comme étalons analytiques par un groupe de laboratoires français.

Ryan P.R. 1973. Ph.D. Thesis Univ. of Keele. The solid geology of the area between Bréhec and Binic, Côtes-du-Nord, France.

Shapiro L., Brannock W.W. 1962. U.S. Geol. Surv. Bull. 1144-A. Rapid analysis of silicate, carbonate and phosphate rocks.

Shaw D.M. 1968. Geochim. Cosmochim. Acta 32, 573-601. A review of K-Rb fractionation trends by covariance analysis.

Steiger R.H., Hart S.R. 1967. Amer. Mineral. 52, 87-116. The microcline-orthoclase transition within a contact aureole.

Sutton J., Watson J. 1957. Proc. Geol. Assoc. 68, 179-204. The structure of Sark, Channel Islands.

Sutton J., Watson J. 1970. Proc. Geol. Assoc. 81, 577-584. The Alderney Sandstone in relation to the ending of plutonism in the Channel Islands.

Taylor, S.R. 1965. In: Physics and Chemistry of the Earth. Vol. 6. Ahrens L.H., Press F., Runcorn S.K., Urey H.C. (Eds.) Pergamon Press, 133-213. The application of trace element data to problems in petrology.

Taylor S.R. 1968. In: Origin and distribution of the elements. Ahrens L.H. (Ed.) Pergamon Press, 559-583. Geochemistry of Andesites.

Tilling R.I. 1968. J. Petrol. 9, 331-357. Zonal distribution of variations in structural state of alkali feldspars within the Rader Creek pluton, Boulder Batholith, Montana.

Vallance T.G. 1969. Proc. Linn. Soc. N.S.W. 94, 8-51. Spilites again: some consequences of the degredation of basalts.

Velde D., Quaglieri N., Kienast J-R. 1971. C.R. Acad. Sci., Paris, D, 273, 607-610. Quelques précisions sur les terrains métamorphiques des Haute Falaises de Jobourg (Manche): présence de disthène relique dans des gneiss d'âge pentévrien.

Vidal P., Auvray B., Cogné J., Hameurt J., Jeannette D. 1971. C.R. Acad. Sci., Paris, D, 273, 132-135. Données géochronologiques sur la série spilitique d'Erquy: problèmes nouveaux à propos du Briovérien de Bretagne septentrionale.

Vidal P., Auvray B., Chauvet J-F., Cogné J. 1972. C.R. Acad. Sci., Paris, D, 275, 1323-1326. L'âge radiométrique de la diorite de Saint-Quay-Portrieux (Côtes-du-Nord). Ses conséquences sur le Briovérien de la baie de Saint Brieuc.

Walsh A., Howie R.A. 1967. Trans. Inst. Min. Metall. B, 76, 119-121. Determination of calcium and magnesium in rocks and minerals by atomic absorption spectrophotometry.

Winterer E.L. 1964. In: Problems in palaeoclimatology, Nairn A.E.M. (Ed.) Interscience N.Y., 159-178. Late Precambrian Pebbly mudstone in Normandy, France: Tillite or Tilloid?

Wright T.L., Stewart D.B. 1968. Amer. Mineral. 53, 38-87. X-ray and optical study of alkali feldspar. I. Determination of composition and structural state from refined unit-cell parameters and 2V.

York D., Farquhar R.M. 1972. The earth's age and geochronology. Pergamon Press.